SNARC AND SNAAC: SPATIAL-NUMERIC ASSOCIATION OF RESPONSE-CODES AND ATTENTIONAL CUING

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SNARC AND SNAAC: SPATIAL-NUMERIC ASSOCIATION OF RESPONSE-CODES AND ATTENTIONAL CUING

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LIST OF SYMBOLS AND ABBREVIATIONS

EEG	Electroencephalogram
ERP	Event-related Potential
LRP	Lateralized Readiness Potential
SNAAC	Spatial-Numeric Association of Attentional Cuing
SNARC	Spatial-Numeric Association of Response Codes

SUMMARY

Comprehending quantity and order information denoted by numbers are important abilities in everyday life in most modern societies. Better understanding of how numbers are psychologically represented can lead to better educational practices. Much psychological evidence suggests that numbers are represented in a spatial format, as in a "mental number line" in which smaller magnitudes are associated with left space and larger magnitudes with right space. This representation can lead to facilitation or interference for selection of a spatially oriented response, such as making a left- or right-hand key-press, or orienting attention to left or right sides of visual space. Two event-related potential (ERP) experiments were conducted to examine effects on response-selection and visuospatial attention resulting from associations between numerical magnitude and spatial coordinates of bimanual responses and attentional orienting. *Experiment 1* examined the time course of response-selection processes as modulated by spatial-numeric associations of response codes (SNARC) in combination with expectancy, in a task of comparing the magnitude of two sequentially presented digits. In SNARC-compatible conditions, participants made a left-hand response to say the second digit was smaller, and a right-hand response to say it was larger, than the first digit. In SNARC-incompatible conditions participants made a right-hand response to say the second digit was smaller, and a left-hand response to say it was larger, than the first digit. The first digit to be compared gave advance information about the likely magnitude of the second digit to be compared, and thus about the likely response to be required.

Behavioral response times (RTs) showed that interference from SNARC-incompatible response mapping was attenuated when the first digit gave complete information about the upcoming second digit and the required response. However, SNARC interference was still evident in ERP covert measures of mental processing. Lateralized readiness potentials (LRPs) showed evidence for SNARC interference at intermediate stages of processing, consistent with a limited amount of ERP research into SNARC effects, when response-cuing provided complete information in advance about the required response. Additionally the non-lateralized P300 showed clear SNARC effects in contrast to previous findings. Results are discussed in terms of a modified "dual-route" model, in which fast activation of task-irrelevant information competes for response-selection with slow activation of information related to task goals. *Experiment 2* examined whether visuospatial attention shifts can be elicited automatically by numerical magnitude, by presenting task-irrelevant visual probes in left or right peripheral visual space following small- or large-magnitude digit pre-cues. Early visual ERPs showed a possible trend for enhancement after small-magnitude digits regardless of visual hemifield in which the probe appeared. Results across experiments suggest that spatialized number representation has different consequences within reference frames for either action or perception.

CHAPTER 1

INTRODUCTION

Quantity and order are two important features of events in the world that can be described by numbers. Comprehending numbers is important for survival and effective action in most contemporary societies. Better understanding of how numbers are represented psychologically and by the brain has potential implications for pedagogy and policy making. Numbers refer to abstract conceptual entities. But how are they represented in the brain? Researchers in cognitive psychology and cognitive neuroscience are increasingly concerned with questions about how human beings derive meaning from experience, think about abstractions, understand concepts, interpret symbols, and construct metaphors (Barsalou, 1999; 2008a; 2008b; Barsalou, Simmons, Barbey & Wilson, 2003). Concepts of "love," "power," or "identity" have no concrete, physical objects as referents. How are such abstract ideas represented in the brain? Traditional approaches in cognitive psychology have asserted that symbols and other abstractions are represented in the brain in a central, amodal, propositional format separated from sensory-motor systems dedicated to perceiving and acting on the environment (Glenberg, 1997; Killeen & Glenberg, 2010). Increasingly however, researchers are considering the general proposal that concepts and other products of the imagination are grounded in the same sensory-motor translations responsible for perception and action (Barsalou, 1999; 2008a; 2008b; Barsalou et al., 2003; Gallese & Lakoff, 2005; Glenberg, 1997; Killeen & Glenberg, 2010).

Whether symbolic and conceptual thought depends on abstract, amodal representations or arises through the development of "perceptual symbol systems" is currently debated (Barsalou, 1999; 2008a; 2008b; Barsalou et al., 2003). Similarly, whether numerical information is represented in an amodal, abstract format is currently debated (Cohen Kadosh & Walsh, 2009; Rips, Bloomfield & Asmuth, 2008). Evidence that numbers are represented in a spatial analog format, such as a "mental number line" has long been found in classic effects such as the "size effect" in which magnitude comparisons are faster for relatively small numbers, and the "distance effect" in which magnitude comparisons are faster when the difference between two numbers is relatively small (Cohen-Kadosh, Lammertyn, & Izard, 2008; Moyer & Landauer, 1967)

It has been proposed that neural representations of number may be opportunistically mapped onto representations for more concrete dimensions of experience, such as space (Dehaene, 1997); similar to other theories about how the abstract concept of time is represented (Boroditsky, 2000; Boroditsky & Ramscar, 2002; Boroditsky & Gaby, 2010). A Theory of Magnitude (ATOM; Bueti & Walsh, 2009; Walsh, 2003a) proposes that attributes of space, time, number, and other quantities are processed by a generalized magnitude estimating system supported by posterior parietal cortex (PPC). Communication between quantity-sensitive parietal neurons and frontoparietal circuits coding response parameters is one hypothesized mechanism for the so-called *spatial-numeric association of response codes* (SNARC; Dehaene, 1997; Dehaene, Bossini & Giraux, 1993; Dehaene et al., 2003; Hubbard, Piazza, Pinel & Dehaene, 2005; Tuduscius & Nieder, 2009) introduced next.

SNARC

The SNARC effect has been reliably observed across a range of experimental paradigms since its discovery in a magnitude comparison task (Dehaene, Dupoux & Mehler, 1990) but has been most often investigated using a *parity* judgment task (Dehaene et al., 1993; Hubbard et al., 2005; Wood & Fischer, 2008; Wood, Willmes, Nuerk & Fischer, 2008). In the parity task of the seminal investigations (Dehaene et al., 1993), participants were instructed to make a left-hand response if a centrally-presented stimulus digit was odd and a right-hand response if it was even (with response-hand-mapping alternating across blocks). Although magnitude information is not strictly necessary to perform parity judgments, responses to small-magnitude digits were faster for left-hand responses (SNARC-compatible) and slower for right-hand responses (SNARC-incompatible); while the reverse pattern was observed for large-magnitude digits (Dehaene et al., 1993). Like other kinds of psychophysical comparisons, SNARC effects were shown to depend on the range of magnitudes not on the absolute magnitudes. The SNARC effect is widely assumed to depend on a spatially directed "mental number line" representation, automatically elicited by numerical stimuli (Dehaene et al., 1993; Hubbard et al., 2005; Wood & Fischer, 2008; Wood et al., 2008). The SNARC effect is thought to provide additional evidence that numbers are represented in a spatial analog format, like the "size effect" and "distance effect" (Cohen-Kadosh et al., 2008; Moyer & Landauer, 1967).

SNARC interference appears similar to the "Simon effect" (Simon & Rudell, 1967) that arises from stimulus-response (S-R) compatibility (Kornblum, Hasbroucq, & Osman,, 1990; Proctor & Cho, 2006). Simon interference occurs when participants must make bimanual responses to stimuli that are lateralized in visual space. Faster right-hand

responses are observed to stimuli in the right visual field versus stimuli in the left visual field. Likewise, left-hand responses are faster to stimuli in the left visual field versus stimuli in the right visual field. SNARC interference appears similar to Simon interference because an irrelevant lateralized stimulus dimension interferes with a lateralized response.

However for the Simon effect the task-irrelevant dimension is explicitly spatial, whereas for the SNARC effect this is not so. In contrast, in SNARC phenomena the spatial dimension is implicit and perhaps only metaphorically related to an oriented number line. Precise relations between SNARC and Simon effects remain to be fully clarified and both types of phenomena may be special cases of even more general S-R compatibility (Proctor & Cho, 2006). However, current evidence tends to the conclusion that SNARC and Simon effects are dissociable (Hubbard et al., 2005; Mapelli, Rusconi & Umiltà, 2003; Rusconi, Turatto, & Umiltà, 2007).

A small number of studies have used ERP to examine SNARC effects on response-selection (Gevers, Ratinckx, De Baene & Fias, 2006; Keus, Jenks & Schwartz, 2005), discussed in the following.

ERP: SNARC in Parity Judgments

Keus and colleagues (2005) examined the *lateralized readiness potential* (LRP) during a parity judgment task. The LRP, recorded at C3/C4 electrodes over pre-motor cortex, is a measure of relative brain activation contralateral versus ipsilateral to the responding hand (Coles, Gratton & Donchin, 1988; Gratton, 1998; Masaki, Takasawa & Yamazaki, 2000; Masaki, Wild-Wall, Sangalis & Sommer, 2004). Thus the LRP can give a real-time picture of brain activation related to making a choice decision that is

made by a left- or right-handed response. The LRP is derived by subtracting ipsilateral from contralateral activation, relative to the responding hand on a given trial, and then averaged over hands. This subtraction method is beneficial because it removes from the ERP activation that is 1) the same across hemispheres and 2) always different across hemispheres. Thus the LRP removes activation that is extraneous to specifically selecting, preparing, and executing a response with a given hand.

Keus and colleagues (2005) examined the LRP time-locked either to the stimulus (S-LRP) or the response (R-LRP). The basic logic behind examining both S-LRP and R-LRP is the following. The S-LRP is assumed to reflect activation related to evaluating the stimulus to a greater extent than activation related to preparing the response. Activation closer to the time of response-preparation/-execution is relatively smeared in the S-LRP, while activation closer to the time of perceiving/evaluating the stimulus is recorded with better fidelity. In contrast, the R-LRP is assumed to reflect activation related to preparing and executing the response to a greater extent than activation related to evaluating the stimulus. Activation closer to the time of perceiving/evaluating the stimulus is relatively smeared in the S-LRP, while activation closer to the time of response-preparation/-execution is recorded with better fidelity. Furthermore, the interval between stimulus-onset and the onset of the S-LRP can be assumed to index the duration of pre-motoric processes leading to response-selection, while the interval between the onset of the R- LRP and the response is assumed to index the duration of subsequent motoric processes involved with response- preparation/execution (see also Coles et al., 1988; Gratton, 1998; Hackley, Schankin, Wohlschlager & Wascher, 2007; Masaki et al., 2000; Masaki et al., 2004).

Following this logic, Keus and colleagues (2005) reasoned that if SNARC interference is localized at some stage after response-selection, perhaps during motoric response preparation, then there should be differences across SNARC-compatible and –incompatible conditions in the R-LRP but not the S-LRP. In contrast, observing SNARC-related effects in the S-LRP would indicate that SNARC interference is localized to an earlier stage, such as pre-motoric response-selection (see also Coles et al., 1988; Gratton, 1998; Masaki et al., 2000; Masaki et al., 2004). This reasoning exemplifies the use of ERP as "modern mental chronometry" (Meyer, Osman, Irwin & Yantis, 1988).

Behavior showed the SNARC effect, i.e., slower RTs for large-magnitude digits requiring a left-hand response compared to those requiring a right-hand response, with the reverse pattern for small-magnitude digits. SNARC-compatible conditions elicited more negative S-LRPs compared to SNARC-incompatible conditions, approximately 300 ms post-stimulus. The authors characterized this result as indicating a pre-motoric response-selection locus for the SNARC effect. However, some differences were observed in the R-LRPs as well. SNARC-incompatible trials elicited greater negativity in the R-LRPs compared to SNARC-compatible trials. However, regardless of SNARC-compatibility, the R- LRPs showed negative deflections at approximately the same time point, 200 ms before response execution, indicating to the authors that SNARC-related interference had been "resolved" prior to the initiation of motoric response-preparation and -execution.

Gevers, Ratinckx and colleagues (2006) likewise examined S-LRP and R-LRP; as well as the non-lateralized P300 component. The P300 is regarded as a neural

correlate of "context-updating" (Dien, Spencer & Donchin, 2004), perhaps also marking the termination of stimulus-evaluation processes, leading to a subsequent response-selection stage (Coles, Gratton, Bashore, Eriksen & Donchin, 1985).

S- LRP onsets were delayed for SNARC-incompatible versus -compatible trials, suggesting that SNARC interference had effects at a relatively early response-selection stage. Notably, initially positive "dips" in the S-LRP for SNARC-incompatible trials were observed, indicating activation of the incorrect response prior to choosing the correct one. Such dips in the S-LRP have been taken to indicate "early communication" between stimulus-evaluation and response-selection systems in the brain (Coles et al., 1988). In contrast, R-LRPs were not significantly different between SNARC-incompatible and -compatible trials, although SNARC-incompatible R-LRP also showed the positive "dip" reflecting pre-response activation of the incorrect response (Coles et al., 1988; Gevers, Ratinckx et al., 2006). These results suggested again that SNARC interference arises and is resolved prior to response preparation/execution; locating response-selection as a potential boundary for the earliest stage that is likely to be affected by SNARC interference.

The non-lateralized P300 component did not differ between SNARC-compatible and SNARC-incompatible conditions. This result suggested that SNARC effects were not operating as early as the conclusion of stimulus evaluation (Coles et al., 1985) or "context updating" (Dien et al., 2004). The authors cautioned however that their null finding for the P300 could have reflected a general lack of sensitivity by this component for distinguishing neural events in intermediate processing stages. Indeed, the P300 is subject to non-specific influences from multiple superimposed signals and there is not yet

any consensus concerning its functional significance (Coles et al., 1985; Dien et al., 2004; Luck, 2005a). Gevers, Ratinckx and colleagues (2006) concluded that SNARC interference was "not resolved at early perceptual stages" (p 66), but rather, at an intermediate stage of response-selection. However, it should be noted that the P300 is viewed as a relatively late or intermediate component, when compared to e.g., truly early visual ERPs like P1 or N1 (Luck, 2005).

To summarize, previous ERP research tends to support the conclusion that SNARC effects are localized to an intermediate "response-selection stage" of mental information processing, which comes after perceptual/semantic stimulus evaluation processes (Gevers, Ratinckx et al., 2006), but before motoric response-preparation/-execution processes (Gevers, Ratinckx et al., 2006; Keus et al, 2005). Thus, SNARC interference is thought to arise and be resolved in a stage of central cognitive processing. However, it can be further asked "how unitary is this cognitive 'response-selection stage'?" One goal of the present research was to address this question.

Theoretical Accounts of SNARC

Based on the evidence for pre-response activation of the incorrect response observed in LRPs, Gevers, Ratinckx and colleagues (2006) argued their findings were inconsistent with a "single-route" serial-stage architecture in which early sensory/perceptual and intermediate decision making processes must be completed before response-selection processes may begin (e.g., Sternberg, 1969; Sanders, 1980). They favored instead a "dual-route" model of the SNARC effect, in which possible responses are activated in parallel, and competition for response-selection is gradually resolved, as evidence accumulates over time in favor of one response versus others. This has been

implemented in a computational model (Gevers, Verguts, Reynvoet, Caessens & Fias, 2006).

The "conditional" route relies on the output of a "verification stage" that evaluates possible responses against task goals (Kornblum et al., 1990). The "unconditional" route is based on correspondences between stimulus- and response-sets (i.e., "dimensional overlap"; Kornblum et al., 1990). Gevers, Ratinckx and colleagues (2006) attributed the LRP positive "dip" (indicating initial activation of the incorrect response) to response-priming via this unconditional route. According to this dual-route framework, the parity task with bimanual response introduces the issue of stimulus-response compatibility precisely because magnitude representations for the stimulus set possess dimensional overlap with representations of possible actions in the response set (Kornblum et al., 1990). The dimension of overlap between stimulus- and response sets in the parity task is thought to be spatially directed like a mental number line.

Similar to the dual-route model proposed by Gevers, Ratinckx and colleagues, a "continuous flow" model of information processing assumes that responses are activated throughout the stimulus evaluation process (Coles et al., 1985). Similarly, an "affordance competition" framework (Cisek, 2007; Cisek & Kalaska, 2010) suggests that the brain continuously specifies response parameters of a range of possible actions in its continuous interactions with world. Response competition for selection plays out within a network of fronto-parietal cortices and sub-cortical structures. Evidence in favor of one action over others accumulates until a threshold is reached, whereupon the selected action is "released" for execution (Cisek, 2007; Cisek & Kalaska, 2010).

It has been proposed that SNARC-related competition for response-selection arises "automatically" when making judgments about numerical information (Gevers, Ratinckx et al., 2006). How might these "automatic" effects be modulated by communicating information about the likely response that is to be executed, in advance of the imperative stimulus? Another goal of the present experiment was to address this question. A recent ERP experiment introduced a suitable procedure for adapting to this question (Scheibe, Schubert, Sommer & Heekeren, 2009), discussed next.

Response-Cuing and Prior Response-Probability

Scheibe and colleagues (2009) communicated advance information about the likely response to be executed in a number comparison task. (However, their investigation was only incidentally concerned with numerical cognition and did not examine possible SNARC-related effects of S-R compatibility). Scheibe and colleagues requested participants to judge which of two digits, presented bilaterally and sequentially, was the numerically larger one, by making a left or right key-press corresponding to the spatial location of the larger digit.

The digit presented first (D1) was selected from the set (1, 3, 5, 7, or 9), was presented either to the left or right of fixation, and remained visible until participants made their number comparison judgment following presentation of the second digit (D2). D2 was presented on the opposite side of fixation and was selected from the set (1-9, excluding the selected value of D1). Therefore, D1 provided varying degrees of advance information during the D1-D2 interval concerning the likelihood that D2 would be the larger or smaller digit. Given the location of D1, its magnitude indicated the probability that a left-hand (or right-hand) response would be required upon presentation of D2

[equal to .50 (when D1 was 5), .75 (when D1 was 3 or 7), or 1 (when D1 was 1 or 9)]. This arrangement allowed comparisons among ERP correlates for response-selection when knowledge of the required response was of differing degrees of certainty in advance of the imperative stimulus. Additionally within the case of intermediate uncertainty, comparisons were possible between responses to validly- and invalidly-cued responses, i.e., when P (Response | D1) = .75 and D2 ultimately required the more or less likely response, respectively.

Scheibe and colleagues (2009) found the LRP time-locked to D1 showed no activation during the D1-D2 interval unless the prior response-probability was equal to 1. The LRP time-locked to D2 showed more graded effects related to prior response-probability given by D1. Additionally, LRPs for invalidly-cued responses showed the positive "dip" typically characterizing initial pre-response activation of an incorrect response, noted earlier in connection with the SNARC effect (Gevers, Ratinckx et al., 2006). Questions about SNARC were not part of the investigation by Scheibe and colleagues, which were focused instead on examining preparation processes during a cue-target interval (or "foreperiod). Nevertheless, their experimental paradigm would seem suitable for addressing the question posed earlier: how would SNARC effects on response-selection, especially indicated by LRP, be modulated by communicating advance information about the likely response?

LRP effects related to prior response-probability (Scheibe et al., 2009) showed some clear similarities to LRP effects related to SNARC-compatibility, reviewed earlier (Gevers, Ratinckx et al., 2006; Keus et al., 2005). Specifically, in the number comparison task the LRP time-locked to the imperative stimulus showed earlier

activation when prior response-probability was certainty, compared to when prior response-probability was lower (Scheibe et al., 2009). Similarly, in the parity task the LRP time-locked to the imperative stimulus digit showed earlier activation when S-R mapping was SNARC-compatible versus –incompatible (Gevers, Ratinckx et al., 2006; Keus et al., 2005). Additionally, "invalidly-cued" responses in the number comparison task and SNARC-incompatible S-R mapping in the parity task each resulted in pre-response positive "dips" in the LRP, indicating initial activation of the incorrect response (Gevers, Ratinckx et al., 2006; Keus et al., 2005; Scheibe et al., 2009). These analogous effects across separate investigations, showing the modulation of LRPs due to either SNARC-compatibility or prior response-probability, motivated the present investigation of how these factors would potentially combine in their effects on the LRP.

Present Research (Experiment 1)

As reviewed above, SNARC-compatibility effects appear for response-selection. Similarly, prior response-probability effects appear for response-selection. However, it remains unclear whether "response-selection" is best characterized as a unitary or multiple construct (Jennings & Van der Molen, 2005). These observations raise the question: how (and when) will effects of prior-response probability and SNARC-compatibility combine, especially in the LRP as an electrophysiological measure of response-selection? Moreover, assuming that SNARC effects are triggered automatically as some have proposed (e.g., Gevers, Ratinckx et al., 2006), would SNARC effects be observed even when response-selection benefits from pre-cuing? Experiment 1 addressed these questions by examining LRPs.

Participants viewed numerical digits presented sequentially in the center of the screen and judged whether the second digit (D2) was larger or smaller than the first digit (D1) by making either left- or right-handed key-press. D1 magnitude communicated the

prior probability of a given response, because participants were aware of the full set of digits which could be presented. SNARC-compatibility was held constant within blocks of trials, and varied across blocks, so that S-R mapping was similarly a present feature of the task environment at the start of each trial.

One question of interest was therefore whether SNARC-compatibility would modulate the prior response-probability effect that was observed in the D1-D2 interval in the previous study by Scheibe and colleagues (2009). Additionally, it was of interest to discover how SNARC-compatibility might combine with prior response-probability, and/or with cue-validity, in the time interval after D2.

CHAPTER 2

METHOD EXPERIMENT 1

This chapter reports information about participants, materials and procedure, for behavioral tasks and electrophysiological recording in Experiment 1.

Participants

25 volunteers (10 females) between the ages of 18 and 40 years (M = 21, SD = 5.07) participated in the experiment and were compensated with pay or partial course credit. All participants had normal or corrected-to-normal vision. 22 participants were right-handed by self-report. The experiment was done with the approval of the Institutional Review Board of Georgia Institute of Technology. Participants gave written informed consent.

Procedure

The experimental session lasted approximately two hours including preparing participants for EEG recording and their subsequent performance of the experimental tasks. Stimuli were presented and behavioral responses were recorded in experimental tasks presented by computer, programmed using e-prime software (Schneider, Eschman & Zuccolotto, 2002). The experiment was performed in a dimly-lit and sound-attenuated booth. The experimenter remained present during the experiment and monitored on-line EEG recordings, to admonish participants as needed to refrain from blinking, moving their eyes, or otherwise introducing signal artifacts by unnecessary movements during trials. Participant head position was controlled by means of a chin-rest so that

participants viewed the experimental stimuli from a constant distance of approximately 57 cm.

Trial sequences and stimuli are depicted in Figure 1. Participants viewed two sequentially presented digits (D1, D2) presented centrally at fixation and then reported whether the second digit (D2) was smaller or larger than the first digit (D1) by making a left- or right-hand key-press. Trials began with a fixation point for a variable amount of time between 500 - 600 ms (in steps of 20 ms), randomly selected on each trial. The fixation point was a white dot against the black background. Then the digit cue (D1) was presented centrally at fixation for 100 ms. D1 was pseudo-randomly selected from the set (1, 3, 7, 9), with the constraint that each value for D1 was selected an equal number of times within blocks. Digit stimuli were displayed approximately 1 cm in height and .5 cm in width, subtending approximately 1º of visual angle with the participant's head positioned approximately 57 cm from the stimulus. The D1 cue was followed by a fixation point for 900 ms, and then the second digit (D2; the imperative stimulus) appeared for 100 ms, followed by a fixation point (for 2000 ms or until response). Values for D2 were pseudo-randomly selected from the set (1, 3, 7, 9), excluding the value selected for D1, and with the constraint that for each value of D1, each possible value for D2 was selected an equal number of times within blocks.

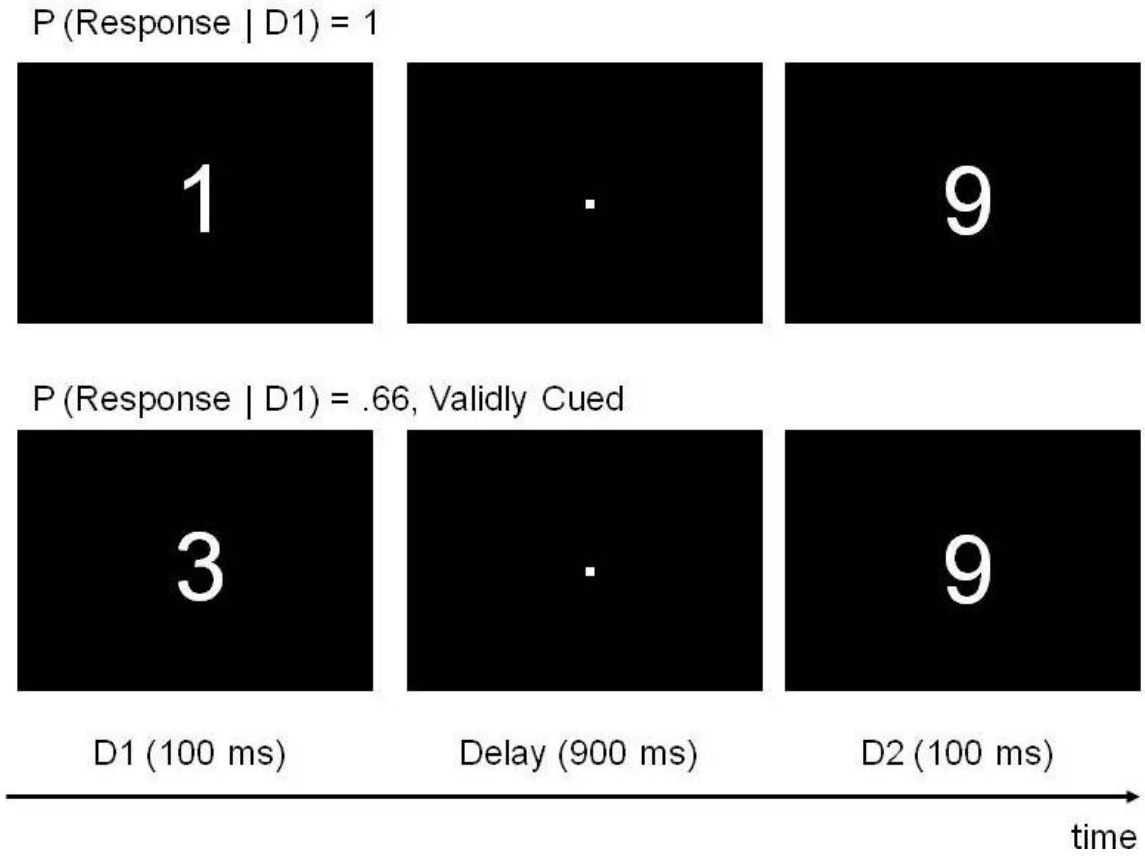

Figure 1. Trial Sequence Experiment 1. Participants reported whether the second digit (D2) was less than or greater than the first digit (D1) by responding with left- or right-handed key-press. "Validly cued" refers to the fact that when prior response-probability was equal to .66, the more likely response was required upon presentation of D2. An "invalidly cued" trial in this case would have presented '1' as D2.

Participants performed the number comparison task in SNARC-compatible or SNARC-incompatible stimulus-response mapping conditions, in two distinct tasks within the experimental session, with task order counterbalanced across participants. On each trial participants used the index fingers of left and right hands, to press respectively the 'Z' or 'N' keys of a standard computer keyboard, to indicate whether D2 was larger (D2 > D1) or smaller (D2 < D1) than D1.

Half the participants first performed 14 blocks (24 trials per block) in the *SNARC-compatible* condition, responding with the index finger of the left hand when D2 < D1, and with the index finger of the right hand when D2 > D1, followed by 14 blocks (24 trials per block) in the *SNARC-incompatible* condition, responding with the right index finger when D2 < D1, and with the left index finger when D2 > D1; Half the participants performed the tasks in the reverse order. The first two blocks of each task were treated as practice blocks and those data were excluded from analyses. Thus there were 288 trials in total in each SNARC-compatibility condition.

In the SNARC-compatible condition, the probability of a left-hand response when D1 = 1 was equal to zero, and the probability of a right-hand response was equal to 1. Conversely when D1 = 9 the probability of a left-hand response was equal to 1, and the probability of a right-hand response was equal to zero. In contrast, in the SNARC-incompatible condition, the probability of a left-hand response when D1 = 1 was equal to 1, and the probability of a right-hand response was equal to zero. Conversely when D1 = 9 the probability of a left-hand response was equal to zero, and the probability of a right-hand response was equal to 1.

Prior response-probability given by D1 was orthogonally varied with SNARC stimulus-response compatibility. In the SNARC-compatible condition, the probability of a left-hand response when D1 = 3 was equal to .33, and the probability of a right-hand response was equal to .66. Conversely when D1 = 7 the probability of a left-hand response was equal to .66, and the probability of a right-hand response was equal to .33. In contrast, in the SNARC-incompatible condition, the probability of a left-hand response when D1 = 3 was equal to .66, and the probability of a right-hand response was equal to .33. Conversely when D1 = 7 the probability of a left-hand response was equal to .33, and the probability of a right-hand response was equal to .66.

There were 144 trials in each SNARC-compatibility condition in which prior response-probability was equal to 1. Likewise, there were 144 trials in each SNARC-compatibility condition in which prior response-probability was equal to .66. Of these, there were 96 trials in each SNARC-compatibility condition in which D2 was "validly cued" by D1. This means that when prior response-probability was equal to .66, the more likely response was in fact required upon presentation of D2. There were 48 trials in each SNARC-compatibility condition in which D2/response was invalidly cued by D1. This means that when prior response-probability was equal to .66, the less likely response turned out to be required upon presentation of D2. [The nesting of "D1 response-cue-validity" within the manipulation of prior response-probability entailed that separate analyses were required to examine SNARC-compatibility with 1) prior response-probability and 2) D1 response-cue-validity.]

Participants viewed error messages for responding incorrectly, responding before presentation of D2, or failing to make a response. Following the response for correct

trials, or the feedback for incorrect trials, the screen became blank for an inter-trial interval lasting 1300 to 1500 ms (in steps of 20 ms), randomly determined on each trial. Participants were instructed to withhold blinks, eye movements, and other unnecessary movements until the inter-trial interval.

EEG Recording and Analysis

Electrophysiological data were recorded using a BioSemi Active-Two amplifier system (Amsterdam, Netherlands) and was digitized at 512 Hz. Scalp potentials were recorded from 32 electrode sites: FP1/2, F7/8, F3/4, Fz, C3/4, Cz, P7/8, P3/4, Pz, T7/8, O1/2, Oz, AF3/4, FC1/2, CP1/2, PO3/4, FC5/6, and CP5/6. Two additional electrodes will serve as reference and ground electrodes. These electrodes were the common mode sense (CMS) and driven right leg (DRL), respectively. Vertical electrooculogram (EOG) was calculated offline as the difference between electrodes positioned above and below the left eye. Horizontal EOG was calculated offline as the difference between electrodes positioned on the outer canthi of the left and right eyes.

EEG data were analyzed using BrainVision Analyzer (Brain Products, Gilching, Germany). Offline, all channels were re-referenced to the algebraic average of the left and right mastoids. Continuous EEG were digitally band-pass filtered from 0.1 to 30 Hz using a zero phase-shift Butterworth filter (12 dB/oct). EEG were segmented into 1200 ms segments beginning 200 ms pre-stimulus and continuing 1000 ms post-stimulus (either D1 or D2). Segments were then baseline corrected by setting the average of the 200 ms pre-stimulus baseline to zero. An ocular correction method was used to remove artifacts due to horizontal eye movements (Gratton, Coles & Donchin, 1983).

Additionally, segments containing activity greater than ± 80 μV in the scalp and VEOG channels were considered artifacts and rejected.

LRPs were calculated and analyzed within two major time intervals during each trial, Post-D1 (averages time-locked to D1), and Post-D2 (averages time-locked to D2). When a left-hand movement was required, EEG/ERP activity from the ipsilateral C3 electrode was subtracted from the activity recorded at the homologous contralateral C4 electrode. The analogous contralateral-minus-ipsilateral subtraction was carried out when a right-hand movement was required. Finally, the contralateral-minus-ipsilateral subtractions for left- and right-hand conditions were averaged together to form the LRP for each condition. (This procedure was done for all lateralized electrode pairs, but the pair C3/C4 was focused on for analyses of the LRP). Mean area amplitudes (in μV) from selected time windows were submitted to statistical analyses.

CHAPTER 3

RESULTS AND DISCUSSION EXPERIMENT 1

In this chapter behavioral results of Experiment 1 are reported first, then electrophysiological results.

Behavioral Results

As noted, when prior response-probability was equal to .66, there was the possibility that D2 could be "invalidly-cued" by D1, i.e., the less likely response given D1 turned out to be the response that was required upon presentation of D2. This nesting of "D1 response-cue-validity" within the manipulation of prior response-probability entailed separate analyses to examine effects of SNARC-compatibility in combination with those of 1) prior response-probability and 2) D1 response-cue-validity. These are reported next in turn, with separate ANOVAs for response time (RT) and response accuracy.

SNARC-Compatibility and Prior Response-Probability

A 2 x 2 repeated-measures ANOVA was conducted, to examine effects of the independent variables SNARC-Compatibility (Compatible, Incompatible) and Prior Response-Probability (.66, 1) on Mean RT as the dependent variable. Only correct trials were included. Only trials in which D1 was a valid cue were included. Results are depicted in Figure 2 (left panel). The effects of SNARC-compatibility and Prior Response-Probability were each significant, F (1, 24) = 12.38, p =.002, η_p^2 = .340, and F

(1, 24) = 98.84, $p < .001$, $\eta_p^2 = .805$, respectively. RTs were faster in SNARC-Compatible versus SNARC-Incompatible conditions ($M = 335.67$, $SE = 22.46$, and $M = 392.81$, $SE = 27.44$, respectively). RTs were faster when Prior Response-Probability was equal to 1 versus when it was equal to .66 ($M = 298.05$, $SE = 27.09$, and $M = 430.43$, $SE = 21.92$, respectively). However, these effects were qualified by their significant interaction, F (1, 24) = 6.04, $p = .022$, $\eta_p^2 = .201$. Post hoc analysis confirmed that the effect of SNARC-Compatibility on RT was larger when Prior Response-Probability was equal to .66 compared to when it was equal to 1 ($M = 79.41$, $SE = 18.98$, and $M = 34.89$, $SE = 18.21$, respectively), t (24) = 2.46, $p = .022$ ($M_d = 44.52$, $SE_d = 18.11$).

A 2 x 2 repeated-measures ANOVA was conducted to examine effects of the independent variables SNARC-Compatibility (Compatible, Incompatible) and Prior Response-Probability (.66, 1), on Mean Proportion-Correct Responses as the dependent variable. Only trials in which D1 was a valid cue were included. Results across conditions are depicted in Figure 2 (right panel). The effect of SNARC-Compatibility was significant, F (1, 24) = 16.14, $p = .001$, $\eta_p^2 = .402$. Responses were more often correct in SNARC-Compatible versus SNARC-Incompatible conditions ($M = .98$, $SE = .006$, and $M = .96$, $SE = .007$, respectively). The effect of Prior Response-Probability was not significant, F (1, 24) = 2.20, $p = .151$, $\eta_p^2 = .084$. The interaction was significant, F (1, 24) = 8.78, $p = .007$, $\eta_p^2 = .268$. Post hoc analysis confirmed that the effect of SNARC-Compatibility on Response Accuracy was larger when Prior Response-Probability was equal to .66 compared to when it was equal to 1 ($M = 0.03$, $SE = 0.01$, and $M = 0.01$, $SE = 0.01$, respectively), t (24) = 2.96, $p = .007$ ($M_d = 0.02$, $SE_d = 0.01$).

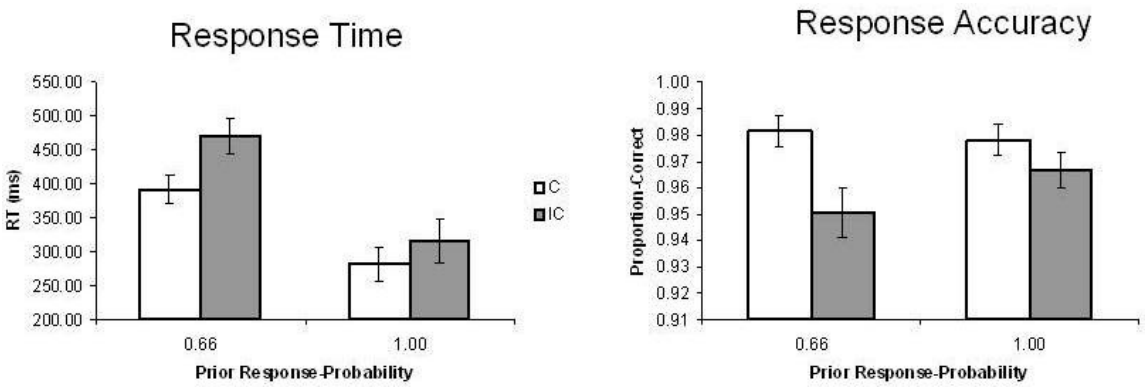

Figure 2. Behavioral Results SNARC and Prior-Response Probability. Response time (left) and response accuracy (right) in Experiment 1, with the factors of SNARC-compatibility and prior response-probability. Legend: *C* means SNARC-compatible, *IC* means SNARC-incompatible.

SNARC-Compatibility and Response Cue-Validity

As noted, the nesting of "D1 response-cue-validity" within the manipulation of prior response-probability entailed that separate analyses were required to examine effects of SNARC-compatibility with those of 1) prior response-probability and 2) D1 response-cue-validity. Therefore, a 2 x 2 repeated-measures ANOVA was conducted, to examine effects of the independent variables SNARC-Compatibility (Compatible, Incompatible) and Cue-Validity (Valid, Invalid) on Mean RT as the dependent variable. Only correct trials were included. Only trials in which Prior Response-Probability was equal to .66 were included. Results across conditions are depicted in Figure 3 (left panel). The effects of SNARC-Compatibility and Cue-Validity were each significant, F (1, 24) = 20.27, p <.001, η_p^2 = .458, and F (1, 24) = 17.77, p < .001, η_p^2 = .425, respectively. RTs were faster in SNARC-Compatible versus SNARC-Incompatible conditions (M = 401.79, SE = 19.79, and M = 485.54, SE = 26.09, respectively). RTs were faster when the response was validly cued by D1 (M = 430.43, SE = 21.92, and M = 456.90, SE = 20.95, respectively). The interaction was not significant, F < 1.

A 2 x 2 repeated-measures ANOVA was conducted to examine effects of the independent variables SNARC-Compatibility (Compatible, Incompatible) and Cue-Validity (Valid, Invalid), on Mean Proportion-Correct Responses as the dependent variable. Only trials in which Prior Response-Probability was equal to .66 were included. Results across conditions are depicted in Figure 3 (right panel). The effects of SNARC-Compatibility and Cue-Validity were each significant, F (1, 24) = 15.06, p = .001, η_p^2 = .386, and F (1, 24) = 9.94, p = .004, η_p^2 = .293, respectively. Responses were more often

correct in SNARC-Compatible versus SNARC-Incompatible conditions (M = .97, SE = .006, and M = .94, SE = .011, respectively). Responses were more often correct when the response was validly cued by D1 (M = .97, SE = .006, and M = .95, SE = .009, respectively). The interaction was not significant, F (1, 24) = 1.10, p = .304, η_p^2 = .044.

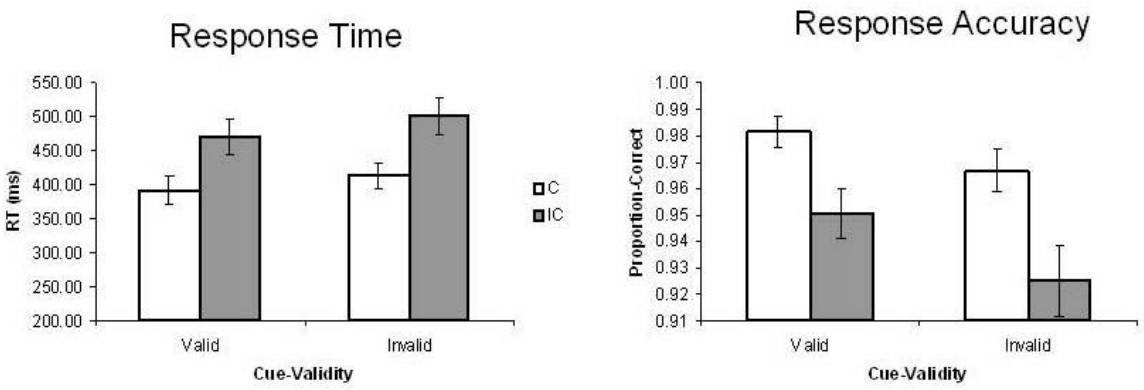

Figure 3. Behavioral Results SNARC and Response-Cue-Validity. Response time (left) and response accuracy (right) in Experiment 1, with the factors of SNARC-compatibility and D1 response-cue-validity. Legend: *C* means SNARC-compatible, *IC* means SNARC-incompatible.

Discussion of Behavioral Results Experiment 1

Behavioral results were consistent with previous separate investigations of SNARC-compatibility and prior response-probability. RTs were faster when stimulus-response mapping was SNARC-compatible compared to when it was SNARC-incompatible, and when prior response-probability was equal to 1 compared to when it was equal to .66. These effects interacted such that the SNARC-compatibility effect was attenuated when prior response-probability was equal to 1, and was exacerbated when it was equal to .66.

Corresponding effects were observed for response accuracy. Participants responded correctly more often when stimulus-response mapping was SNARC-compatible compared to when it was SNARC-incompatible, and when prior response-probability was equal to 1 compared to when it was equal to .66.

These effects interacted such that the SNARC-compatibility effect was attenuated when prior response-probability was equal to 1, and was exacerbated when it was equal to .66. Moreover, responses were faster when the response was validly cued by D1 compared to when it was invalidly cued. Notably, SNARC-compatibility did not interact with D1 response-cue-validity in either RT or accuracy. Overall, results for response accuracy do not provide evidence of speed-accuracy tradeoffs that would complicate interpretation of the RTs.

The interaction observed in RT between SNARC-compatibility and prior response-probability would suggest according to some cognitive psychology accounts that these factors therefore modulate the system at a common processing stage, most probably "response-selection." However, behavioral measures alone cannot show the dynamics of response-selection in real-time. Therefore, electrophysiological data were examined to provide further insight into the time course of response-selection.

ERP Results

ERPs were examined in two broad time intervals – the interval between D1 and D2 (D1-D2) and the interval following the presentation of D2 (Post-D2), separately for each condition made up by the factorial combination of SNARC-Compatibility, Prior Response-Probability, and Cue-Validity. As noted earlier, the nesting of "D1 response-cue-validity" within the manipulation of prior response-probability entailed that separate analyses were required to examine effects of SNARC-compatibility with those of 1) prior response-probability and 2) D1 response-cue-validity. Only correct trials were included. LRPs across conditions are shown in Figure 4, from -200 ms before D1 to 1800 ms after D1 to give a picture of activation continuously over the course of the trial. For statistical analyses as well as visual presentation, LRPs were time-locked to either D1 (Figure 5), D2 (Figure 6), or the response (Figure 7). For improved visualization, high-frequency noise was additionally removed from the data before graphing, using a low-pass filter set at 10 Hz.

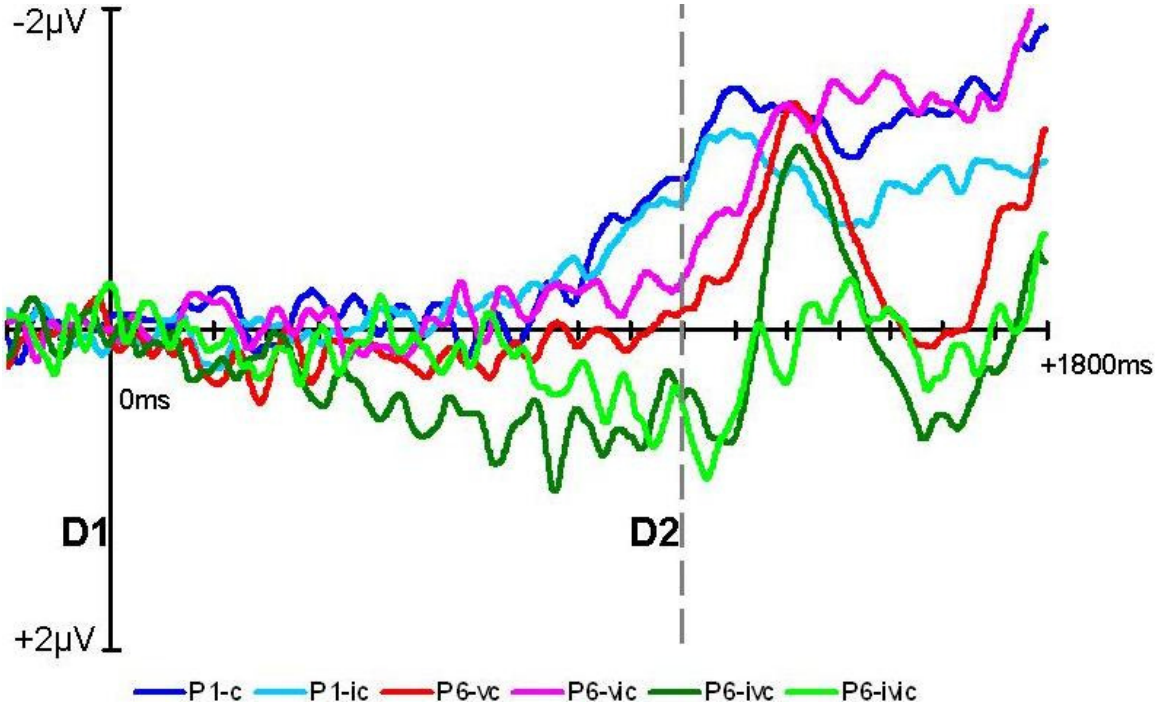

Figure 4. LRP Time-Locked to D1. LRPs time-locked to D1 across Experiment 1 conditions, from -200 ms prior to D1 to +1800 ms after D1. D1 onset = 0 ms, unit =100 ms. Legend: *P1-c* prior response-probability = 1/SNARC-compatible; *P1-ic* prior response-probability = 1/SNARC-incompatible; *P6-vc* prior response-probability = .66/validly-cued/SNARC-compatible; *P6-vic* prior response-probability = .66/validly-cued/SNARC-incompatible; *P6-ivc* prior response-probability = .66/invalidly-cued/SNARC-compatible; *P6-ivic* prior response-probability = .66/invalidly-cued/SNARC-incompatible.

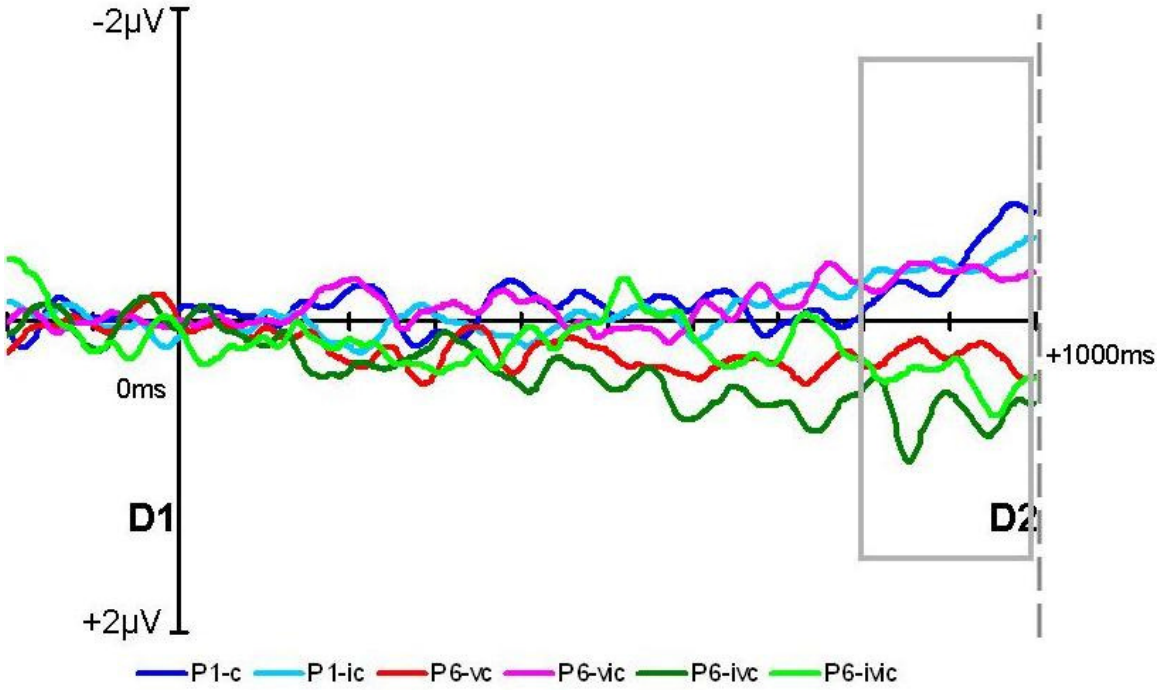

Figure 5. LRPs recorded from C3/4 in the D1 – D2 Interval. LRPs from the C3/4 electrode pair across Experiment 1 conditions, from -200 ms before D1 until D2 onset (+1000 ms after D1). D1 onset = 0 ms (dashed vertical line), unit = 100 ms. The gray box indicates the time window in which mean LRP amplitudes were compared (800-1000 ms post-D1; -200-0 ms pre-D2). Legend: As in Figure 4.

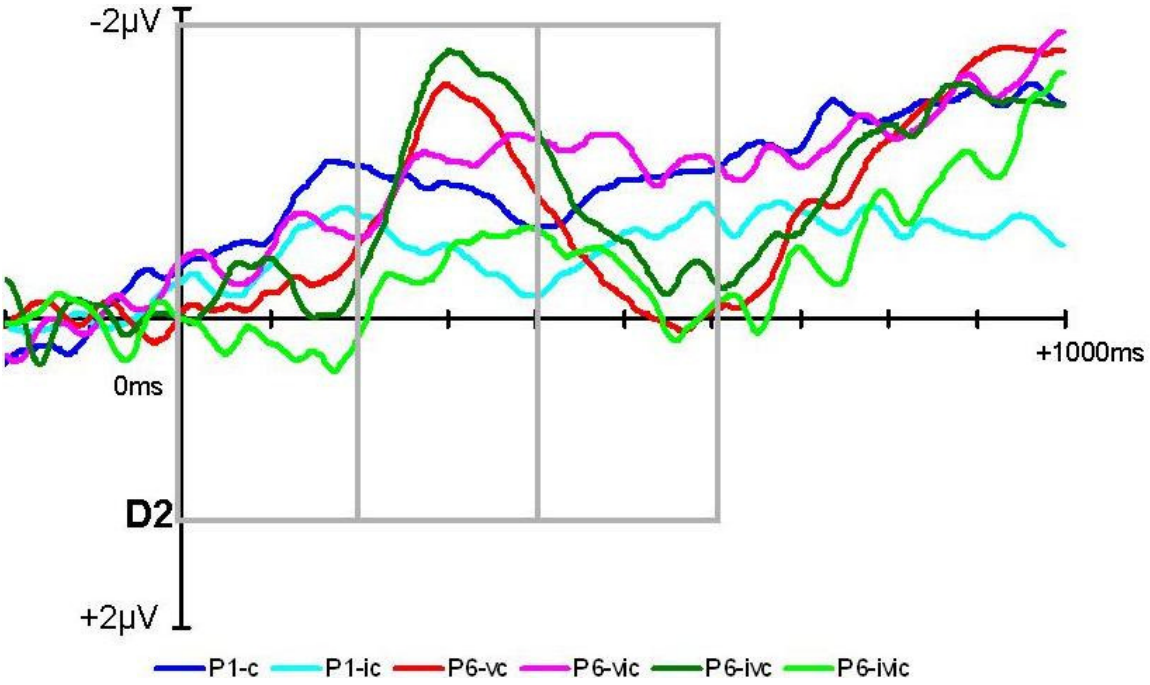

Figure 6. LRP Time-Locked to D2. LRPs across Experiment 1 conditions, from -200 ms before D2 to +1000 ms after D2. D2 onset = 0 ms (y-axis), unit = 100 ms. The gray boxes indicate the three time windows in which mean area amplitudes were compared (0-200 ms post D2, 200-400 ms post-D2, and 400-600 ms post-D2). Legend: As in Figure 4.

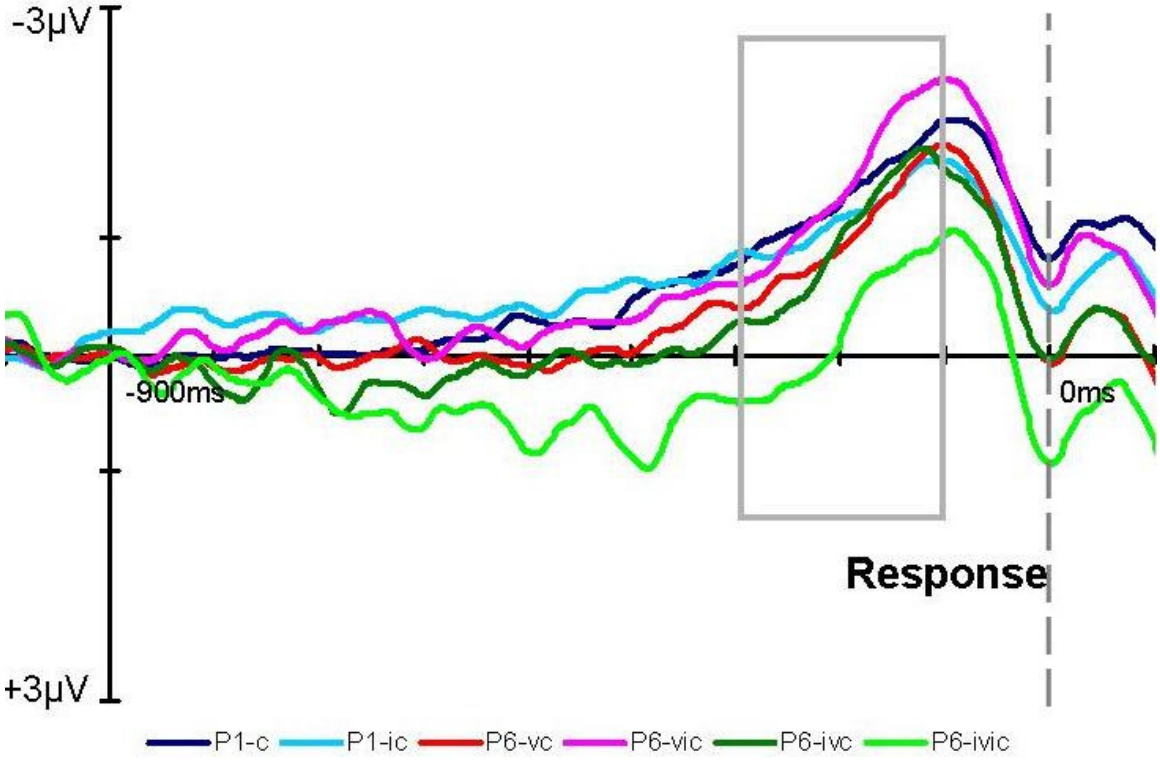

Figure 7. LRP Time-Locked to Response. Response-locked LRPs across Experiment 1 conditions, from -1000 ms before the response to +100 ms after the response. Response = 0 ms (dashed vertical line), unit = 100 ms. Waveforms were baseline-corrected during the time interval -1000 ms to -900 ms before response offset. Box indicates time window (-300 to -100 ms) in which LRP slopes were computed for each individual for mean comparisons across conditions. Legend: As in Figure 4.

D1-D2 Interval

Mean LRP amplitudes in the D1-D2 interval for the C3/4 electrode pair are shown in Figure 5 (see also Figure 8 for pre-subtraction waveforms). The mean area LRP amplitude (μV) was examined in the D1-D2 interval in the smaller time interval 800 – 1000 ms post-D1 (200 ms pre-D2). This time interval was chosen based on previous research (Scheibe et al., 2009). Noting that it was unknown to the participant at this point in the trial whether the required response would be validly-cued or invalidly-cued by D1, the analysis combined data from validly- and invalidly-cued trials when prior response-probability was equal to .66.

A 2 x 2 repeated-measures ANOVA was conducted to examine effects of the independent variables SNARC-Compatibility (Compatible, Incompatible) and Prior Response-Probability (.66, 1) on mean area LRP amplitude, in the time interval 200 ms – 0 ms before D2. Only correct trials were included. The main effect of SNARC-Compatibility was not significant, $F < 1$. The main effect of Prior Response-Probability was significant, F (1, 24) = 7.44, p = .012, η_p^2 = .237. Mean area amplitude was more negative when Prior Response-Probability was equal to 1 compared to when it was equal to .66 (M = -.38, SE = .17, and M = .23, SE = .13, respectively). The interaction was not significant, F (1, 24) = 1.56, p = .224, η_p^2 = .061. Scalp distributions for pre-subtraction ERPs in this time window are shown in Figure 9. Scalp distributions for post-subtraction ERPs in this time window are shown in Figure 10. These show a strong frontal negativity slightly anterior to C3/C4 electrodes, only when prior response-probability was equal to 1, suggesting that advance response-cuing supported earlier selection of the correct response before the appearance of D2. There is not a clear pattern of difference between scalp distributions for SNARC-compatible and –incompatible conditions, but

SNARC-compatible scalp distributions show a posterior positivity that is not present in SNARC-incompatible.

These results are consistent with those reported by Scheibe et al. (2009) and are straightforwardly understood as a result of providing complete versus partial advance information about the response to be required. Notably, SNARC-compatibility did not show significant effects in the LRP observable before the appearance of D2, even though stimulus-response mapping was completely known to participants from the start of every trial. This suggests a possible limitation for the claim that SNARC-induced response-competition is an automatic outcome of processing numerical information or judging magnitude (e.g., Gevers, Ratinckx et al., 2006). For example, if SNARC effects on response-selection were completely automatic, they might have been observable after the D1 response cue, even when prior response-probability was equal to 1, at the point when participants were able to initiate response-selection based on the information provided by the D1 cue alone. However, this was not found. Instead, SNARC effects were observed only subsequent to the appearance of the imperative stimulus D2 (shown in the following sections). This might mean that that the mental number line concept became activated only when it was necessary to make a magnitude judgment about a presently appearing D2 stimulus, and not necessarily as soon as magnitude information is processed to interpret the D1 response-cue and anticipate the upcoming D2 stimulus.

Curiously, the LRP in the D1-D2 interval for trials in which the response was invalidly cued appeared positive-going, especially in the SNARC-Compatible condition (Figure 4, Figure 5, and Figure 8). Mean area amplitude for this condition was significantly different from zero, t (24) = 2.64, p = .004 (M = .593, SE = .225), in the time interval examined in the preceding ANOVAs. This result is somewhat paradoxical because participants would not have known prior to the appearance of D2 whether or not the response was validly cued. It should have been expected rather, that LRPs for validly and invalidly cued responses in this time interval would have appeared much the same.

However, this anomaly might be explained as the spurious product of noise, noting that a maximum of 48 trials would have contributed to ERPs for trials in which responses were invalidly cued. This number would have been further reduced due to incorrect responses (which were more frequent when responses were invalidly cued), as well as premature responses (or failure to make a response). That the LRPs were relatively noisier for these conditions is evident by visual inspection. Furthermore, the positive-going wave for invalidly cued responses did not reappear as a significant effect in the LRPs time-locked to D2, nor did it appear in the response-locked LRPs, at which points participants would have known whether the response had been validly or invalidly cued by D1. The positive-going deflection in the waveforms is not clearly apparent in the scalp distributions either. These considerations suggest that the positive-going LRPs in the D1-D2 interval for invalidly cued trials may have been spurious.

On the other hand, even if this result is taken as face value as a "real" effect, there is no need to appeal to some sort of "precognition" (Bem, 2011) to explain it. The participant did not know in the D1-D2 interval whether a given trial was validly or invalidly cued. Nevertheless, the ERPs "know" this in their retrospective analyses. Invalidly cued trials were relatively rare, and the ERPs only reflect trials in which performance was correct (no errors or premature responses). Error responses were more frequent in invalidly cued trials. Thus the averages for invalidly cued trials are likely disproportionately influenced by a kind of "selection bias" that disproportionately highlights what was distinctive about correct performance. These waveforms reflect what people were doing when they performed the task correctly. A positive-going deflection in the LRP is usually taken to reflect early activation of the incorrect response, to be over-ridden later by cognitive control processes. This interpretation is most often applied to LRPs time-locked to the imperative stimulus or to the response. However, the present situation the positive-going deflection occurs in the LRP time-locked to the response pre-cue, and does not re-appear in later instantiations of the LRP (shown in

subsequent sections of this paper). This might reflect early activation of the incorrect response that is later suppressed. Alternatively, this might be interpreted here as reflecting an inhibitory mechanism for preventing premature responses in advance of the imperative stimulus D2. It is likely that this mechanism would be disproportionately contributing to invalidly cued trials that were restricted to trials in which performance was correct. In this light, the positive-going deflection in this time interval for invalidly cued trials may be more than a mere anomaly or spurious product of noise, but rather an unexpected finding meriting further exploration in future research—perhaps it is evidence for an inhibitory mechanism preventing premature responses.

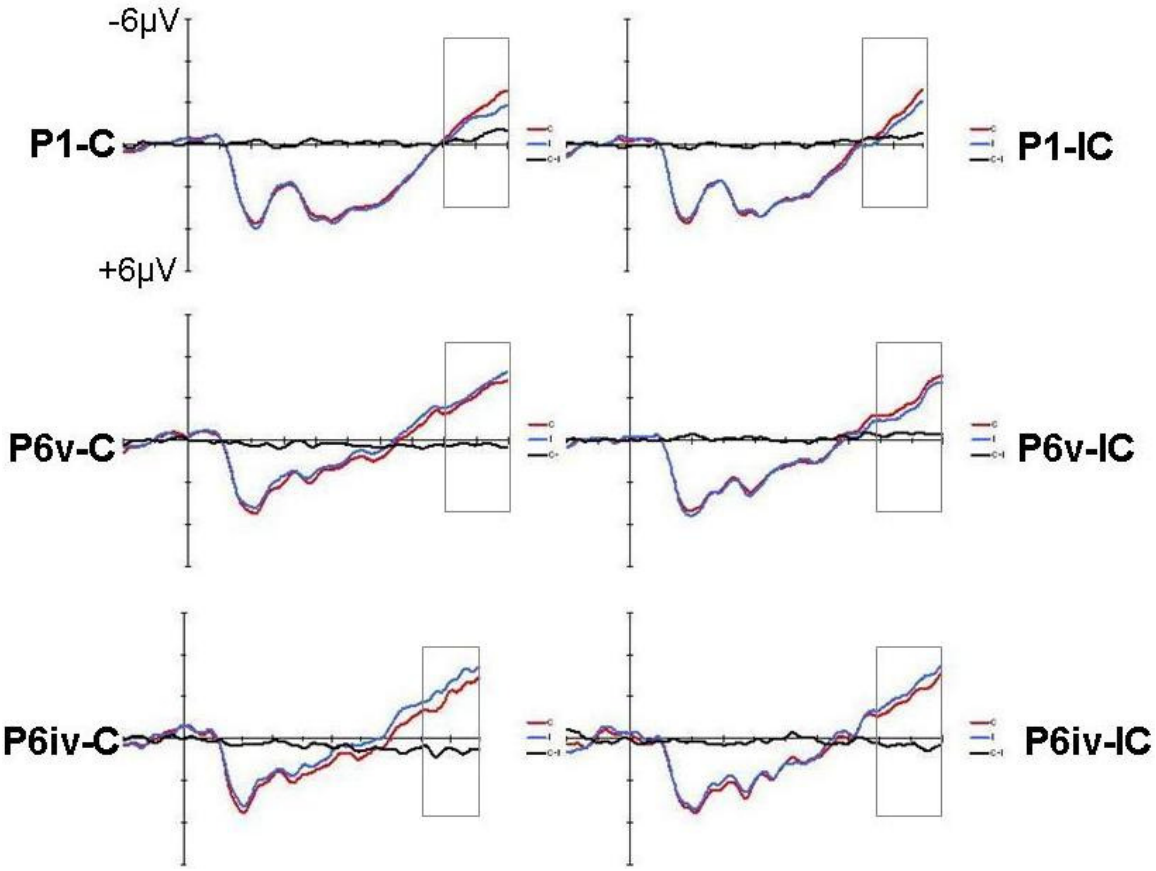

Figure 8. Pre-and Post-Subtraction Waveforms Time-Locked to D1. C3/C4 electrodes. Red = Contralateral, Blue = Ipsilateral, and Black = Contralateral – Ipsilateral (the LRP). Time depicted on x-axis (-200 ms to +1000 ms post-D1 onset). Voltage (μV) depicted on y-axis (range -6 to +6 for all panels). D1 occurs at time 0 ms (y-axis crossing). Unit = 100 ms. Boxes indicate time window 200 ms before D2, in which Prior Response-Probability main effect was observed in LRP.

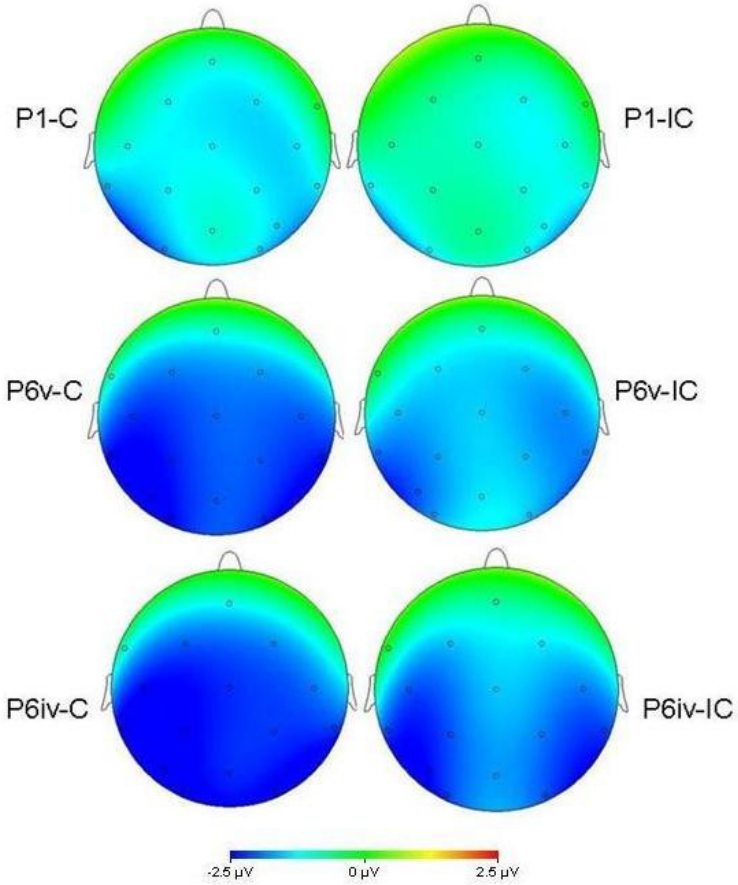

Figure 9. Pre- Subtraction Scalp Distributions Time-Locked to D1. Scalp distributions across conditions 200 – 0 ms before D2 for pre-subtraction ERPs. Contralateral and ipsilateral hemispheres are arbitrarily depicted on scalp maps respectively on the right and left sides.

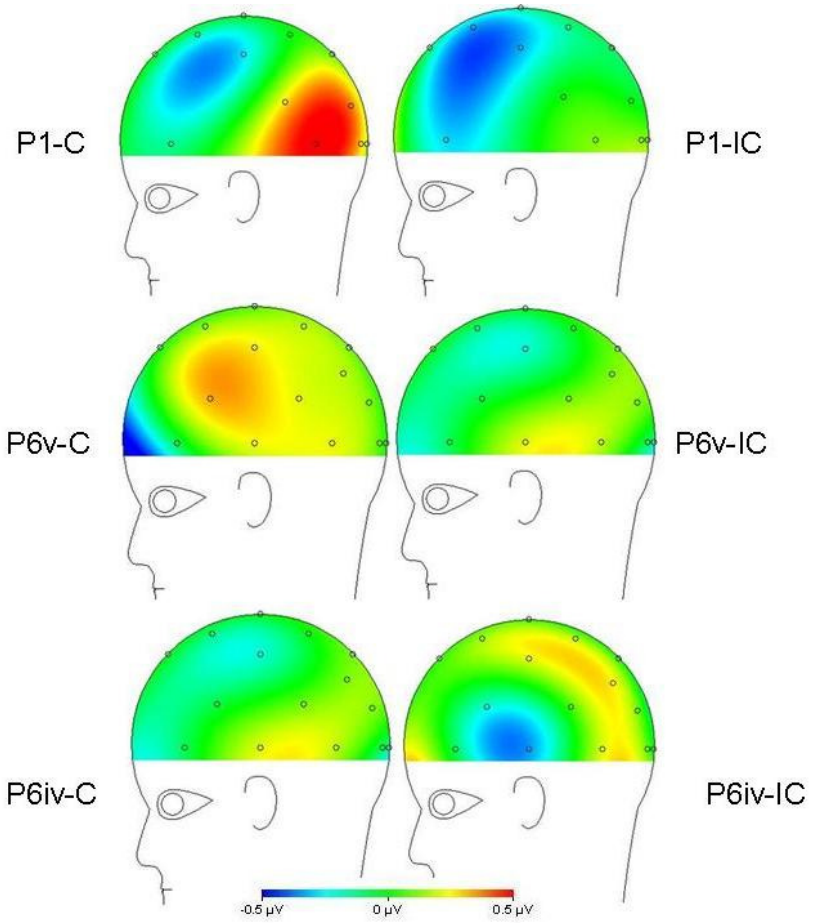

Figure 10. Post-Subtraction Scalp Distributions Time-Locked to D1. Scalp distributions across conditions 200 – 0 ms before D2 for post-subtraction (contralateral minus ipsilateral) ERPs. The left side of the head is depicted arbitrarily.

Post-D2 Interval

(See Figure 6; and for pre-subtraction waveforms, see Figure 11). 2 x 2 repeated-measures ANOVAs were conducted to examine effects of the independent variables SNARC-Compatibility (Compatible, Incompatible) and Prior Response-Probability (.66, 1) on mean area LRP amplitude (μV) after presentation of D2. Within the broad "post-D2" time range, LRPs were examined specifically during three shorter time intervals, 0 – 200 ms, 200 – 400 ms, and 400 – 600 ms post-D2. These time intervals were chosen to in order to examine the post-D2 LRPs during the time in which most behavioral RTs were observed, and to continue the interval scheme established in analysis of the D1-D2 interval. Furthermore, the time window 200 – 400 ms post-D2 was chosen to overlap with previous research, in which SNARC-related effects were observed in the LRP approximately 300 ms post-stimulus (Keus et al., 2005; Gevers, Ratinckx et al., 2006).

An omnibus ANOVA with Time Interval (0-200ms, 200 -400 ms, 400 -600ms) as a factor revealed significant interactions with SNARC-Compatibility, F (2, 23) = 8.19, p = .001, η_p^2 = .254, and with Prior Response-Probability, F (2, 23) = 7.24, p = .002, η_p^2 = .232. ANOVAs were performed separately for each time interval to clarify these interactions. The Time Interval factor did not interact with Cue-Validity, Fs < 1. However, for completeness and consistency, ANOVAs with the Cue-Validity factor were examined separately for each time interval as well.

As noted for the analyses of behavioral responses, the nesting of "D1 response-cue-validity" within the manipulation of prior response-probability entailed that separate analyses were required to examine effects in the LRPs, of SNARC-compatibility in

combination with effects of 1) prior response-probability and 2) D1 response-cue-validity. Thus only trials in which D1 was a valid cue were included in analyses examining combined effects of SNARC-Compatibility and Prior Response-Probability.

Moreover, separate 2 x 2 repeated-measures ANOVAs were conducted to examine effects of the independent variables SNARC-Compatibility (Compatible, Incompatible) and Cue-Validity (Valid, Invalid) on mean area LRP amplitude after presentation of D2, separately during three time intervals, 0 – 200 ms, 200 – 400 ms, and 400 – 600 ms post-D2. Only trials in which Prior Response-Probability was equal to .66 were included in analyses examining combined effects of SNARC-Compatibility and Cue-Validity. The separate ANOVAs including SNARC-compatibility in combination with effects of 1) prior response-probability and 2) D1 response-cue-validity are reported in turn in successive paragraphs, within each section treating the analyses of the separate post-D2 sub-intervals (0 – 200 ms, 200 – 400 ms, and 400 – 600 ms post-D2).

<u>0 – 200 ms</u>

In the ANOVA examining SNARC-Compatibility in combination with Prior Response-Probability, the main effect of SNARC-Compatibility was not significant, F (1, 24) = 1.38, p =.252, η_p^2 = .054. The main effect of Prior Response-Probability was not significant, $F < 1$. The interaction was not significant, F (1, 24) = 2.20, p = .151, η_p^2 = .084.

In the ANOVA examining SNARC-Compatibility in combination with Cue-Validity, the main effect of SNARC-Compatibility was not significant, F (1, 24) = 2.75, p =.110, η_p^2 = .103. The main effect of Cue-Validity was not significant, $F < 1$. The

interaction of SNARC-compatibility and Cue-Validity was not significant, F (1, 24) = 3.32, p = .080, η_p^2 = .122.

200 – 400 ms

In the ANOVA examining SNARC-Compatibility in combination with Prior Response-Probability, the main effect of SNARC-Compatibility was significant, F (1, 24) = 5.22, p =.031, η_p^2 = .179. Mean area amplitude was more negative when stimulus-response mapping was SNARC-Compatible compared to when it was SNARC-Incompatible (M = -1.04, SE = .21, and M = -0.62, SE = .13, respectively). The main effect of Prior Response-Probability was not significant, F (1, 24) = 2.81, p =.107, η_p^2 = .105. The interaction was not significant, $F < 1$.

LRPs in the 200 – 400 ms interval following the appearance of D2 showed effects of SNARC-compatibility but not of prior response-probability. LRPs were more negative in the SNARC-compatible versus SNARC-incompatible conditions. This result is very consistent with a previous finding by Keus and colleagues (2005) using a parity judgment task, in which the stimulus-locked LRP was more negative for SNARC-compatible versus –incompatible trials, approximately 300 ms post-stimulus. Therefore the present result confirms previous findings showing that SNARC interference arises at intermediate processing stages that are probably related to response-selection. Here, this result might also suggest that SNARC-incompatibility exerted residual inhibiting effects on response-selection after the appearance of D2, regardless of prior response-selection afforded by response-cuing. Alternatively, this might mean that that interference due to the mental number line concept became activated only when it was necessary to make a magnitude judgment about a presently appearing D2 stimulus, and not necessarily as soon as magnitude information was processed to interpret the D1 response-cue and anticipate the upcoming D2 stimulus.

In the ANOVA examining SNARC-Compatibility in combination with Cue-Validity, the main effect of SNARC-Compatibility was not significant, F (1, 24) = 1.00, p = .326, η_p^2 = .040. The main effect of Cue-Validity was significant, F (1, 24) = 13.03, p =.001, η_p^2 = .352. Mean area amplitude was more negative when the response was validly cued compared to when it was invalidly cued by D1 (M = -1.20, SE = .19, and M = -0.66, SE = .17, respectively). The interaction of SNARC-compatibility and Cue-Validity was not significant, F (1, 24) = 2.50, p = .127, η_p^2 = .094.

An effect of D1 response-cue validity was also observed in this interval, in which LRPs were more negative when the response was validly- versus invalidly-cued by D1. This straightforwardly illustrates greater facilitation of the correct response when events indeed occurred as expected. Scalp distributions for pre-subtraction ERPs in this time window are depicted in Figure 12. These show that there is a strong posterior positivity, probably related to the P300 component, for all conditions except when prior response-probability was equal to 1 and stimulus-response mapping was SNARC-incompatible, in which it is weaker but still very much present. Also, the LRP is nicely visible here as the asymmetry in the plot around the C3/4 electrode pair. Scalp distributions for post-subtraction waveforms are depicted in Figure 13. These very clearly show greater frontal-central negativity in SNARC-compatible conditions. Also, the maximal negativities appear somewhat anterior to C3/C4 electrodes when prior response-probability was equal to .66.

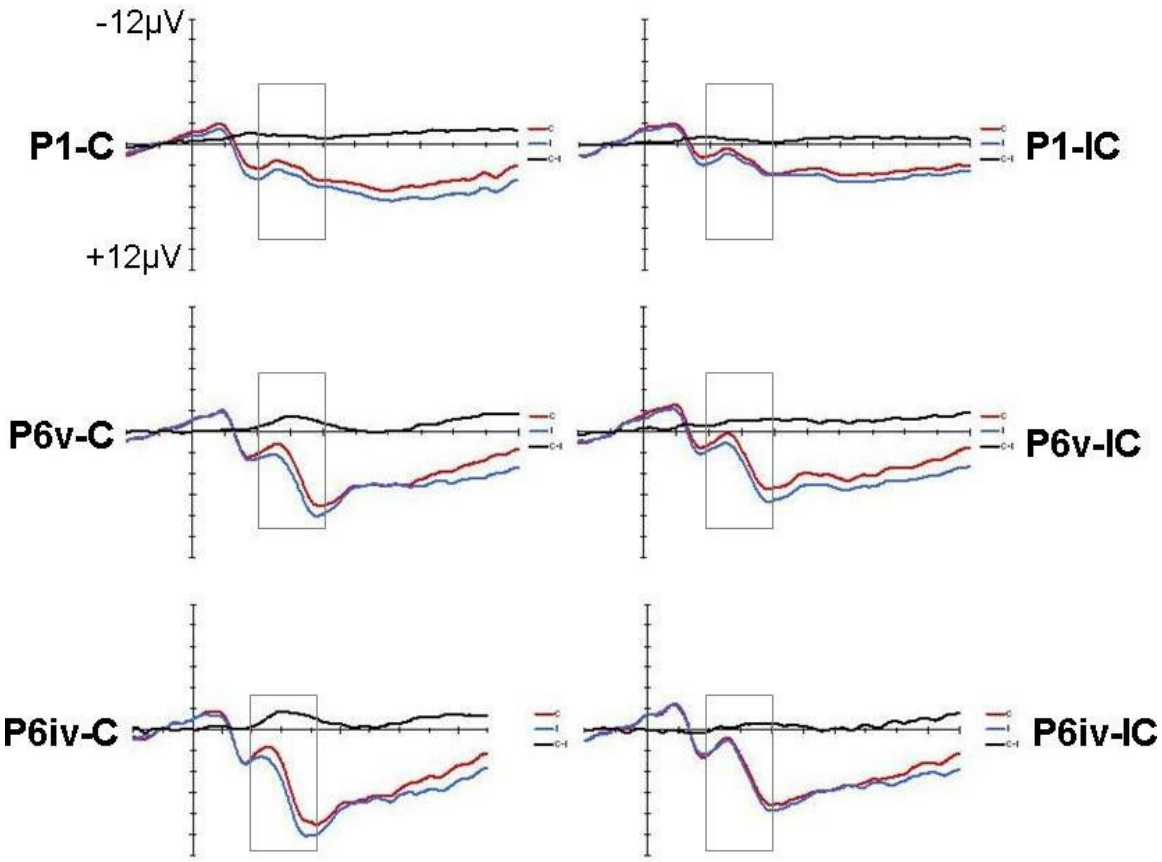

Figure 11. Pre- and Post-Subtraction Waveforms Time-Locked to D2. C3/C4 electrodes. Red = Contralateral, Blue = Ipsilateral, and Black = Contralateral – Ipsilateral (the LRP). Time depicted on x-axis (-200 ms to +1000 ms post-D2 onset). Voltage (μV) depicted on y-axis (range -12 to +12 for all panels). D2 occurs at time 0 ms (y-axis crossing). Unit = 100 ms. Boxes indicate time window 200 – 400 ms post-D2, in which SNARC main effect was observed in LRP.

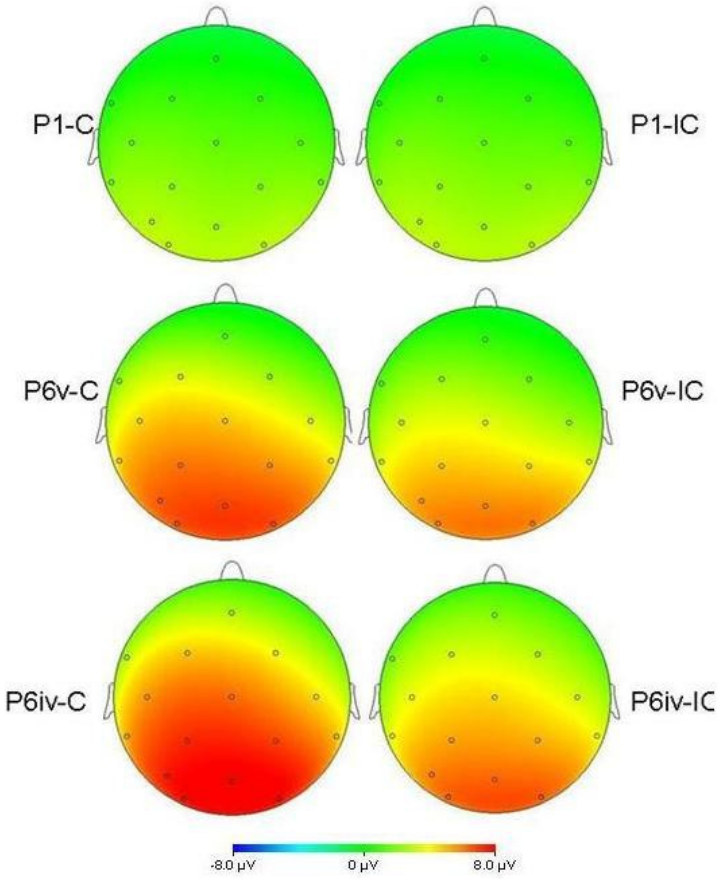

Figure 12. Pre-Subtraction Scalp Distributions 200 – 400 ms Post -D2. Scalp distributions across conditions 200 – 400 ms post-D2 for pre-subtraction ERPs. Contralateral and ipsilateral hemispheres are arbitrarily depicted on scalp maps respectively on the right and left sides.

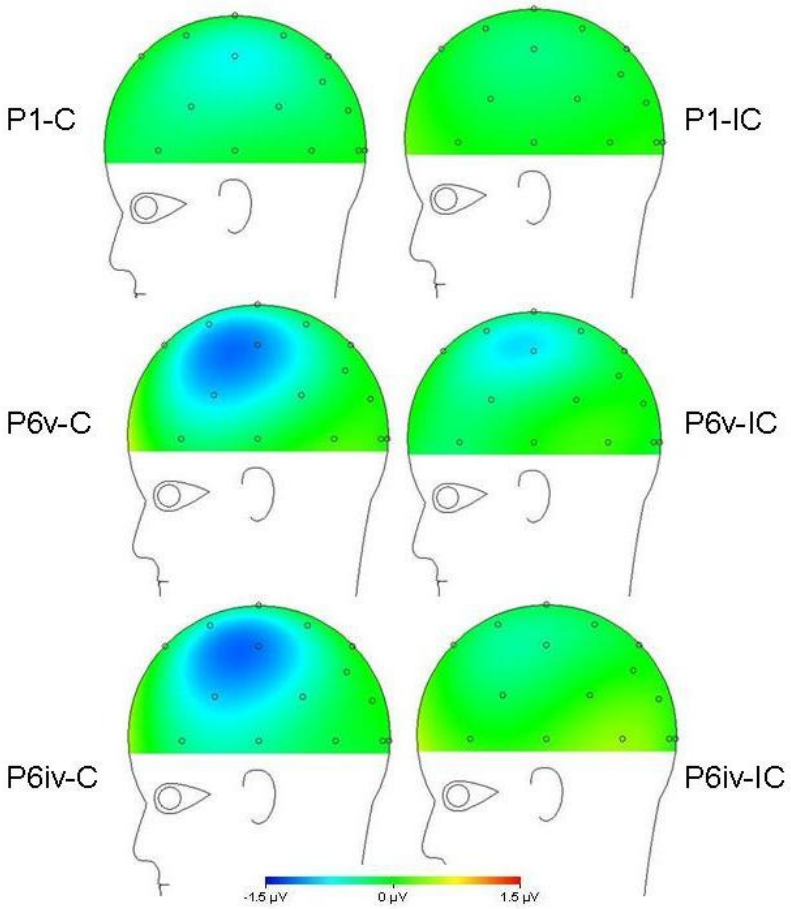

Figure 13. Post-Subtraction Scalp Distributions 200 – 400 ms Post -D2. Scalp distributions across conditions 200 – 400 ms post-D2 for post-subtraction (contralateral minus ipsilateral) ERPs. The left side of the head is depicted arbitrarily.

400 – 600 ms

In the ANOVA examining SNARC-Compatibility in combination with Prior Response-Probability, the main effect of SNARC-Compatibility was not significant, $F < 1$. The main effect of Prior Response-Probability was not significant, F (1, 24) = 3.25, p = .084, η_p^2 = .119. The interaction was significant, F (1, 24) = 6.20, p = .020, η_p^2 = .205. Post-hoc analysis showed that mean area amplitude was more negative when stimulus-response mapping was SNARC-Incompatible versus SNARC-Compatible, when Prior Response-Probability was equal to .66 (M = -1.07, SE = .34, and M = -.23, SE = .26, respectively), t (24) = -3.21, p = .008 (M_d = -.85, SE_d = .26). In contrast, mean area amplitude did not differ between SNARC-Incompatible and SNARC-Compatible conditions when Prior Response-Probability was equal to 1 (M = -.47, SE = .18, and M = -.82, SE = .18, respectively), t (24) = 1.20, p = .480 (M_d = .34, SE_d = .29). Visually inspecting the Figures 6 and 11, the LRP time-locked to D2 appeared to resolve into a clear peak in SNARC-compatible conditions when prior response-probability was equal to .66, but not so in SNARC-incompatible conditions. This might also reflect competition for response-selection related to SNARC interference, especially in a condition in which there was greater uncertainty in advance of the imperative stimulus D2.

In the ANOVA examining SNARC-Compatibility in combination with Cue-Validity, the main effect of SNARC-Compatibility was not significant, $F < 1$. The main effect of Cue-Validity was not significant, F (1, 24) = 2.48, p =.129, η_p^2 = .094. The interaction was significant, F (1, 24) = 4.79, p = .039, η_p^2 = .166. Post-hoc analysis showed that mean area amplitude was more negative when stimulus-response mapping was SNARC-Incompatible versus SNARC-Compatible, when the response was validly

cued by D1 (M = -1.07, SE = .33, and M = -.22, SE = .25, respectively), t (24) = -3.21, p = .008 (M_d = -.85, SE_d = .26). In contrast, mean area amplitude did not differ between SNARC-Incompatible and SNARC-Compatible conditions when D2 was invalidly cued by D1 (M = -.55, SE = .33, and M = -.25, SE = .26, respectively), t (24) = .83, p = .830 (M_d = .30, SE_d = .36).

In the interval 400 – 600 ms after the appearance of the imperative stimulus D2, an interaction of SNARC-compatibility and prior response-probability was observed in the LRP time-locked to D2. When prior response-probability was equal to .66, LRPs were more negative when stimulus-response mapping was SNARC-incompatible versus -compatible; but did not differ across SNARC-compatibility conditions when prior response-probability was equal to 1. Likewise, in the same interval an interaction of SNARC-compatibility and response-cue-validity was observed in the LRP. LRPs were more negative when stimulus-response mapping was SNARC-incompatible versus compatible, when the response was validly-cued by D1. These interacting effects appearing late in the stimulus-locked LRPs are complex to interpret, and are likely related to an earlier LRP onset for trials when D1 response-cues gave complete information about the upcoming D2/response.

Scalp distributions for pre-subtraction ERPs in this time window are depicted in Figure 14. These show further strengthening of the posterior positivity, possibly related to the P300 component. The difference between prior response-probability conditions is evident here, reflecting the fact that there was more uncertainty to resolve in when prior response-probability was less than certain, resulting in a bigger P300 regardless of response-cue-validity.

Scalp distributions for post-subtraction waveforms are depicted in Figure 15. These show a complex pattern of distributions across conditions. Maximal negativities appear by this time interval to be posterior to C3/C3 electrodes when prior response-probability was equal to 1. In contrast, maximal negativities appear more frontally when

prior response-probability was equal to .66, with strong posterior positive maxima appearing as well, especially in SNARC-compatible conditions. Thus, when viewed together as a sequence, the post-subtraction scalp maps from -200 ms before D2 to +600 ms after D2 show a clear anterior-posterior transition for maximal negativities when response pre-cuing provided complete advance information about the correct response. When advance information was less certain, maximal negativities appeared later and had not shifted toward posterior areas by 600 ms after the imperative stimulus D2.

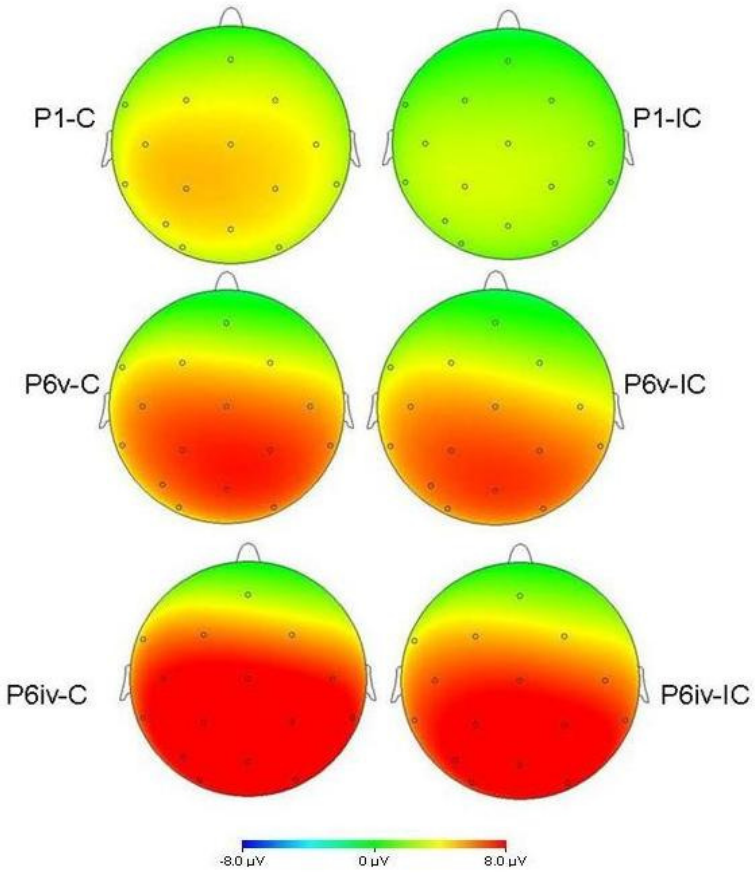

Figure 14. Pre-Subtraction Scalp Distributions 400 – 600 ms Post -D2. Scalp distributions across conditions 400 - 600 ms post-D2 for pre-subtraction ERPs. Contralateral and ipsilateral hemispheres are arbitrarily depicted on scalp maps respectively on the right and left sides.

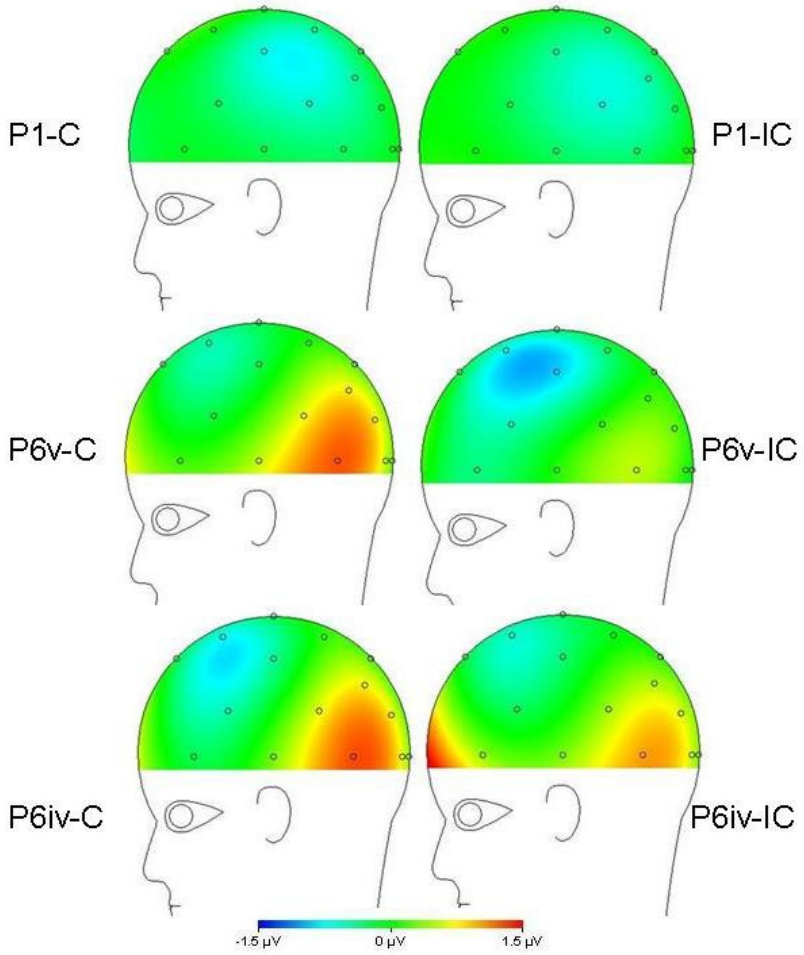

Figure 15. Post-Subtraction Scalp Distributions 400 – 600 ms Post -D2. Scalp distributions across conditions 400 – 600 ms post-D2 for post-subtraction (contralateral minus ipsilateral) ERPs. The left side of the head is depicted arbitrarily.

Response-Locked LRPs

(See Figure 7; and for pre-subtraction waveforms, see Figure 16). To further clarify the time course of effects on response-selection and –execution in the interval after D2, LRPs were examined as time-locked to the response. Data were segmented into intervals from -1000 ms before the response to +100 ms after the response. Following previous research (Scheibe et al., 2006), the time interval -1000 ms to -900 ms before response offset was chosen as the baseline period.

Amplitude

Mean area amplitude was examined for the response-locked LRP in the time interval -200 ms to 0 ms preceding the response. In the ANOVA examining SNARC-Compatibility in combination with Prior Response-Probability, the main effect of SNARC-Compatibility was not significant, F (1, 24) = 1.64, p = .213, η_p^2 = .064. The main effect of Prior Response-Probability was not significant, $F < 1$. The interaction was not significant, F (1, 24) = 2.88, p = .102, η_p^2 = .107. These results mean that expectancy and SNARC interference were not effective for amplitude during late response-execution phases of performance.

In the ANOVA examining SNARC-Compatibility in combination with Cue-Validity, the main effect of SNARC-Compatibility was not significant, Fs < 1. The main effect of Cue-Validity was significant F (1, 24) = 6.23, p = .020, η_p^2 = .206. Mean area amplitude was more negative when responses were validly cued compared to when they were invalidly cued (-1.573 versus -.841, respectively). The interaction was not significant, F (1, 24) = 2.51, p = .126, η_p^2 = .095. These results meant that when prior expectancy was violated, by the appearance of the less likely D2, late response-execution processes were inhibited, as reflected in amplitude differences.

The waveform for SNARC-incompatible trials in which responses were invalidly cued suggests a positive-going wave preceding the response-locked LRP, which could

mean initial activation of the incorrect response. However, although positive, mean area amplitude for this condition in the time interval -500 ms to -300 ms preceding the response was not significantly different from zero, t (24) = 1.46, p = .146 (M = .5102, SE = .348).

Response-locked LRPs did not show SNARC effects in amplitude. This is consistent with previous research showing that SNARC interference is resolved prior to motoric response-execution (Gevers, Ratinckx et al., 2006; Keus et al., 2005). Though visible to inspection, the positive deflection for invalidly cued trials was not significantly different from zero in the response-locked LRPs. Participants would have known at this point in the trial whether expectations that had been established by the D1 cue were confirmed or violated by the imperative stimulus D2. That the signal-to-noise ratio was weaker for ERPs during invalidly cued trials is evident to inspection and is directly attributable to the relative rarity of such trials.

Slope

LRP slopes (μV/ms) were examined, to serve as indices of the rate of lateralized activation build-up in favor of the correct response. The LRP slopes in the interval from -300 to -100 ms before the response were calculated by fitting regression lines to the data for each individual. Scalp distributions for pre-subtraction ERPs in this time window are depicted in Figure 13. Average LRP slopes in this interval were compared in ANOVAs.

Scalp distributions for pre-subtraction waveforms for ERPs time-locked to the response, for the time window in which LRP slopes were computed, are shown in Figure 17. These show increasing posterior positivity when prior response-probability was equal to .66. Scalp distributions for post-subtraction waveforms for ERPs time-locked to the response, for the same time window, are shown in Figure 18. These show maximal difference negativities over C3/C4 electrodes, somewhat indistinguishably across conditions except when responses were invalidly cued and stimulus-response mapping was SNARC-incompatible.

In the ANOVA examining SNARC-Compatibility in combination with Prior Response-Probability, the main effect of SNARC-Compatibility was not significant, $F < 1$. The main effect of Prior Response-Probability was significant, $F\ (1, 24) = 7.61$, $p = .011$, $\eta_p^2 = .241$. The mean LRP slope was steeper (more negative) when Prior Response-Probability was equal to .66 compared to when it was equal to 1 (-.009 versus -.005, respectively). The interaction was not significant, $F\ (1, 24) = 3.71$, $p = .066$, $\eta_p^2 = .134$. Mean slopes across these factors are presented in Figure 19. These results suggest a faster build-up of activation in favor of the correct response when prior response-probability was equal to .66. This is likely related to a later initiation of response-selection in these conditions, necessitating a faster response-execution to maintain a relatively constant rate of responding overall.

In the ANOVA examining SNARC-Compatibility in combination with Cue-Validity, neither the main effects of SNARC-Compatibility nor Cue-Validity, nor the interaction, were significant, Fs < 1. These results mean that response-cue-validity did not affect the rate of activation build-up for late response-execution, even when responses were invalidly cued.

The LRPs time-locked to responses did not show SNARC effects, which is consistent with the limited amount of previous ERP research into SNARC (Gevers, Ratinckx et al., 2006; Keus et al., 2005). Notably, the effect of prior response-probability was evident at even this late stage of response-related processing. LRP slopes, obtained for each individual, were on average steeper (more negative) when prior response-probability was equal to .66 versus when it was equal to 1. This result can be interpreted by noting that participants in RT experiments generally try to maintain a relatively constant rate of responding overall (Laming, 1979). This fact suggests that when complete information about the upcoming response was provided in advance, responses could be executed "more leisurely" when response-selection had been mostly accomplished earlier; and that when response-selection was delayed by reduced advance

information, response-execution was more rapidly performed to maintain a relatively constant rate of response.

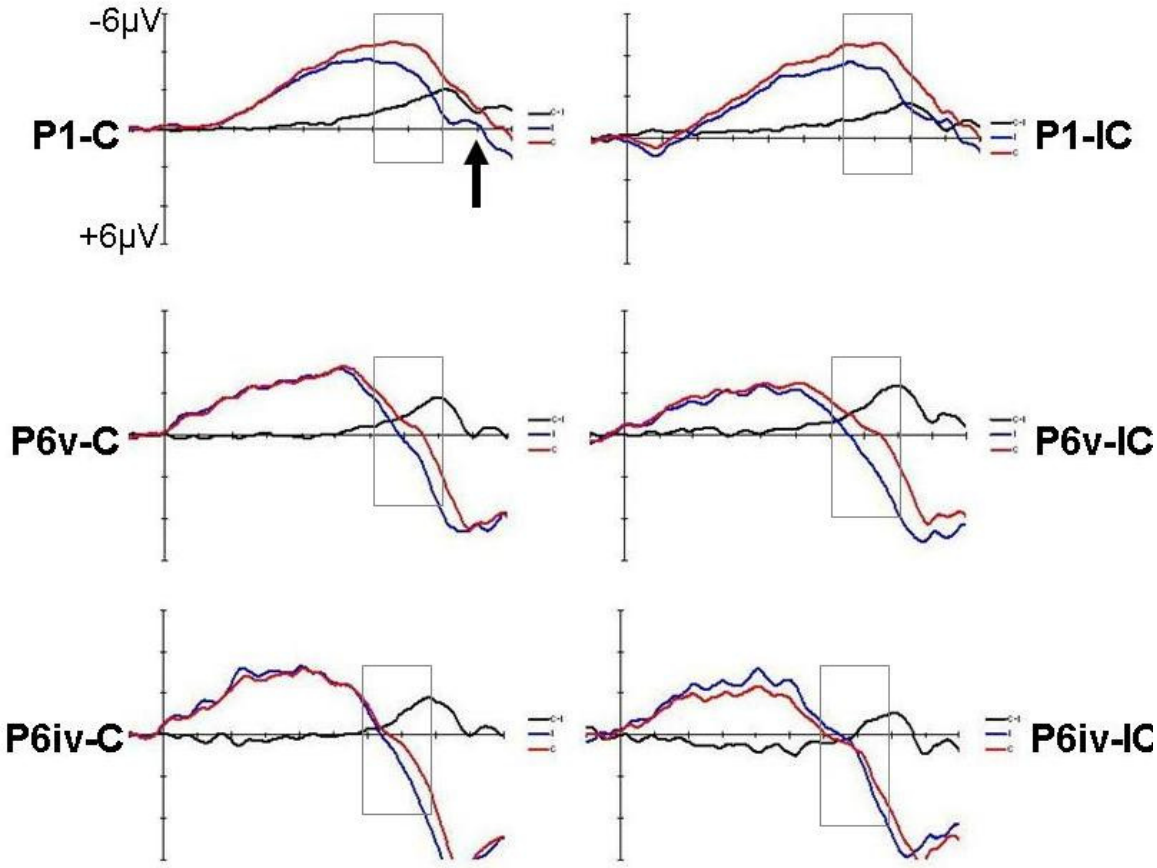

Figure 16. Pre- and Post-Subtraction Waveforms Time-Locked to Response. C3/C4 electrodes. Red = Contralateral, Blue = Ipsilateral, and Black = Contralateral – Ipsilateral (the LRP). Time depicted on x-axis (-1000 ms before response offset, indicated by arrow in upper left panel, to +100 after). Time unit = 100 ms. Voltage (μV) depicted on y-axis (range -6 to +6 for all panels). Boxes indicate time window (-300 to – 100 ms) time window in which individual slopes were fitted for comparisons.

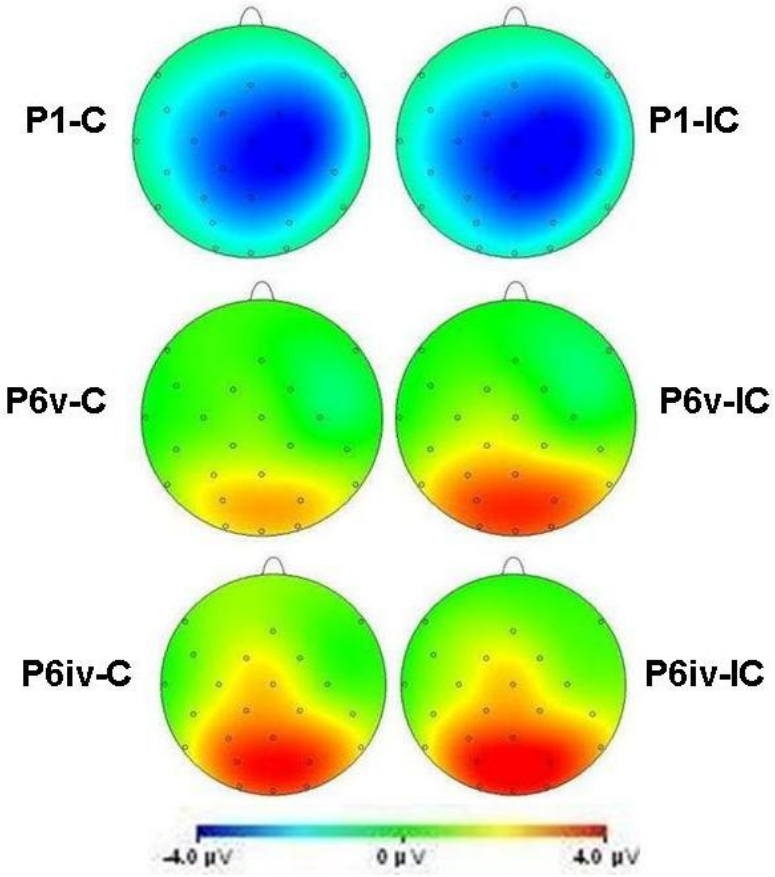

Figure 17. Pre-Subtraction Scalp Distributions Time-Locked to Response. Scalp distributions across conditions for pre-subtraction ERPs time-locked to response, in the indicate -300 to – 100 ms time window in which individual slopes were fitted for comparisons. Contralateral and ipsilateral hemispheres are arbitrarily depicted on scalp maps respectively on the right and left sides.

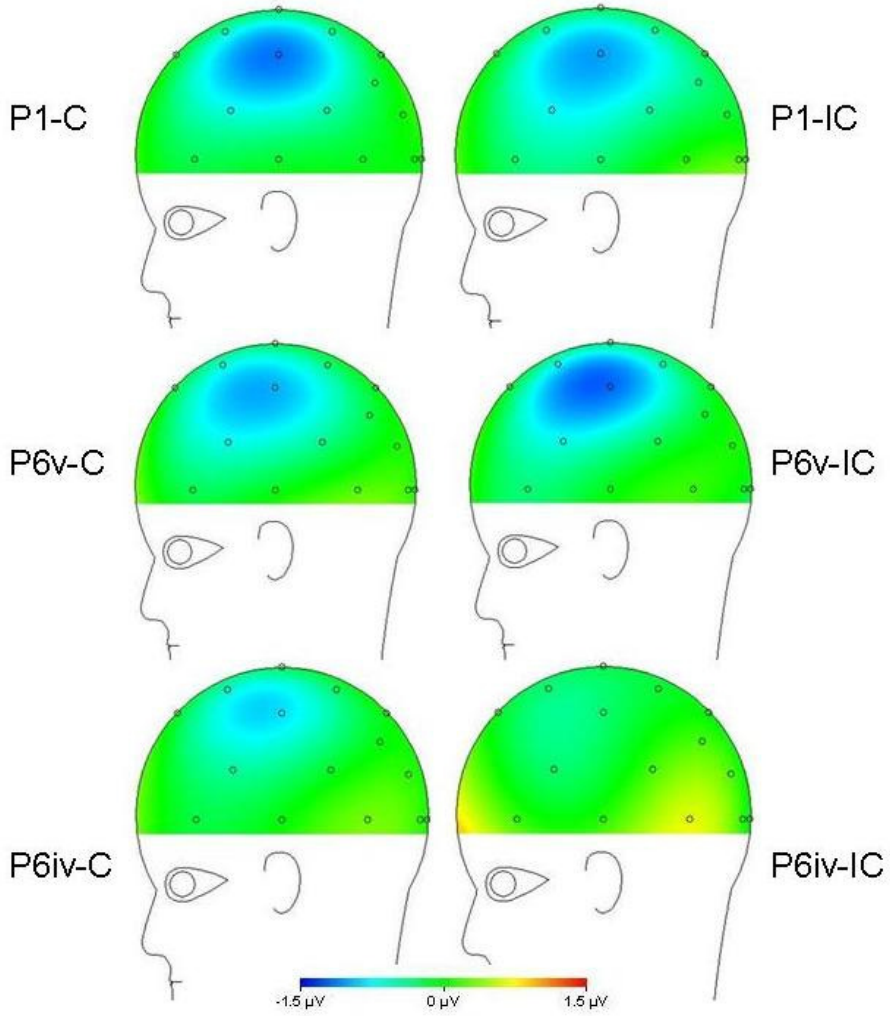

Figure 18. Post-Subtraction Scalp Distributions Time-Locked to Response. Scalp distributions across conditions of post-subtraction (contralateral minus ipsilateral) ERPs time-locked to the response, in the time window in which LRP slopes were computed. The left side of the head is depicted arbitrarily.

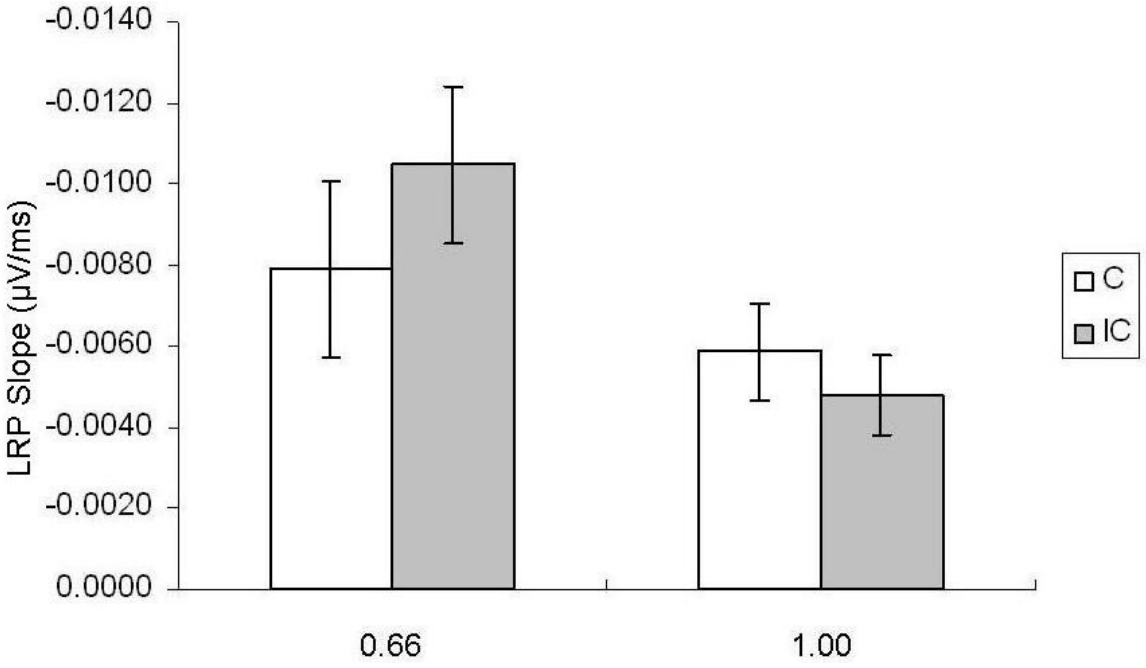

Figure 19. Mean Slopes for LRPs Time-Locked to Response. Mean slopes across conditions for response-locked LRPs in time interval -300 to -100 ms before response termination. White columns = SNARC-Compatible (C), Gray columns = SNARC-Incompatible (IC). Prior Response-Probability represented on x-axis. Slopes were significantly steeper when Prior Response-Probability was equal to .66.

Correlations between LRP Slopes and Behavioral RTs

To investigate whether LRP slopes were functionally meaningful, correlation with behavioral RTs were examined. Notably, LRP slopes when Prior Response-Probability was equal to .66 were significantly correlated with behavioral RTs in some conditions. Specifically, steeper (more negative) LRP slopes when responses were validly cued (SNARC-compatible) were predictive of faster RTs in the same condition, $r = .403$, $p = .046$. Furthermore, steeper (more negative) LRP slopes when responses were invalidly cued (SNARC-Compatible) were predictive of faster RTs in the same condition, $r = .444$, $p = .026$. Additionally, steeper (more negative) LRP slopes when responses were validly cued (SNARC-Compatible) were predictive of faster RTs when Prior Response-Probability was equal to 1 (SNARC-Compatible), $r = .524$, $p = .007$. Additionally, faster RTs when Prior Response-Probability was equal to 1 (SNARC-Compatible), were associated with steeper (more negative) LRP slopes when responses were invalidly cued (SNARC-Incompatible), $r = .406$, $p = .044$. Scatterplots depicting these significant correlations between LRP slope and RT variables are presented in Figure 20. These results mean that LRP slopes were functionally meaningful and related to behavioral performance.

No other significant relationships between LRP slopes and RTs were observed, although RTs across all conditions were significantly and positively associated amongst each other (rs ranging from .597 to .928, ps < .05), suggesting there was sufficient systematic variance in RTs to yield significant correlations across conditions. For comparison purposes, a scatterplot depicting an example non-significant correlation between LRP slope and RT variables is presented in Figure 21. This demonstrates that the failure to observe significant correlation in this case was not due to a lack of variance in one variable or the other per se; but rather, was due to a lack of systematic variance shared between variables.

That the LRP slopes were functionally meaningful is supported by significant correlations with the behavioral RTs, specifically in SNARC-compatible conditions. In light of the fact that no significant SNARC effects were observed for LRP slopes when averaged over individuals, it is intriguing that LRP slopes shared significant systematic variance with RTs only in SNARC-compatible conditions. This result suggests the possibility of hitherto unobserved SNARC effects on relatively late response-execution processes, observable here at the level of individual differences, which may have been obscured in previous investigations that examined data only at the group level.

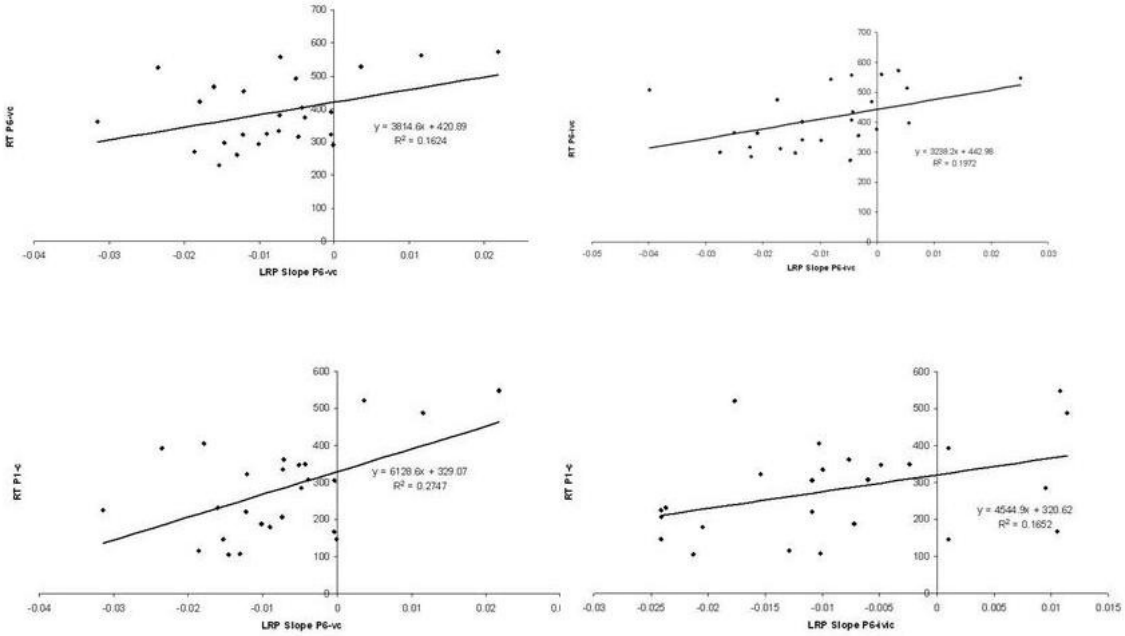

Figure 20. Scatterplots: LRP Slopes Predicting RTs. Slopes for response-locked LRPs (x-axis) predicting RTs (y-axis). *Upper Left*: LRP slopes Prior Response-Probability = .66 responses validly cued (SNARC-Compatible), predicting RTs in same condition. *Upper Right*: LRP slopes Prior Response-Probability = .66 responses invalidly cued (SNARC-Compatible), predicting RTs in same condition. *Lower Left*: LRP slopes Prior Response-Probability = .66 responses validly cued (SNARC-Compatible), predicting RTs Prior Response-Probability = 1 (SNARC-Compatible). *Lower Right*: LRP slopes Prior Response-Probability = .66 responses invalidly cued (SNARC-Incompatible), predicting RTs Prior Response-Probability = 1 (SNARC-Compatible).

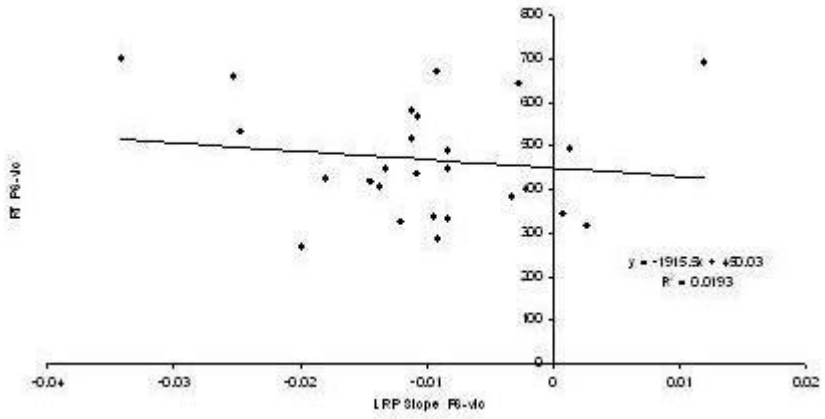

Figure 21. Scatterplots: Example Non-Significant Correlation between LRP Slopes and RTs. Example of non-significant relationship between slopes for response-locked LRPs (x-axis) and RTs (y-axis). LRP slopes Prior Response-Probability = .66 responses validly cued (SNARC-Incompatible), predicting RTs in same condition.

P300

To further clarify neural responses in the Post-D2 interval, mean area amplitude for the non-lateralized ERP was examined at a posterior central electrode (Pz), in the time window 300 – 600 ms post-D2 onset, corresponding to the P300 component. (See Figure 22).

In the ANOVA examining SNARC-Compatibility in combination with Prior Response-Probability, the main effect s of SNARC-Compatibility and Prior Response-Probability were each significant , F (1, 24) = 10.38, p = .004, η_p^2 = .302., and F (1, 24) = 54.71, p < .001, η_p^2 = .695, respectively. Mean area amplitude was more positive in SNARC-Compatible versus SNARC–Incompatible conditions (7.26 versus 6.14, respectively), and when Prior Response-Probability was equal to .66 versus when equal to 1 (8.68 versus 4.71, respectively). The interaction was not significant, F (1, 24) = 1.02, p = .320, η_p^2 = .041.

In the ANOVA examining SNARC-Compatibility in combination with Cue-Validity, the main effect s of SNARC-Compatibility and Cue-Validity were each significant, F (1, 24) = 6.45, p = .018, η_p^2 = .212, and F (1, 24) = 38.11, p < .001, η_p^2 = .614, respectively. Mean area amplitude was more positive when responses were invalidly cued versus validly cued (10.96 versus 8.67, respectively). The interaction was not significant, F (1, 24) = 3.26, p = .084, η_p^2 = .120.

The non-lateralized P300 component showed effects of prior response-probability, response-cue-validity, and also (surprisingly) SNARC-compatibility. The effects of Prior Response-Probability and Cue-Validity on the P300 are relatively straightforward to interpret. When the D1 cue gave complete information about the magnitude of the upcoming D2, there was little "context updating" to do when D2 eventually appeared. This was reflected as a relatively flat but positive waveform. In contrast, when the D1 cue gave only partial information about the magnitude of the upcoming D2, there was indeed much "context updating" to do when D2 eventually

appeared. This was reflected as a more positive waveform with a clear peak. This was especially the case when expectations that had been established by D1 were ultimately violated by D2, i.e., when responses were invalidly cued by D1 magnitude (e.g., D1 = 7, D2 = 9). (Note too that the P300 is sensitive to stimulus frequencies, which can also explain the higher amplitudes evoked by invalidly cued D2 stimuli, i.e., events that were relatively rare). These results suggest parietal involvement in representing prior response-probability, or expressed in more psychological terms, "expectancy."

The experiment produced the novel finding that P300 amplitude was more positive in SNARC-compatible versus –incompatible conditions. The P300 results in the present work show that SNARC interference resulted in a reduced cortical response overall to the imperative stimulus D2, regardless of stimulus frequencies or expectations established by D1 magnitude.

It is likely that the discrepancy between findings is related to the difference in how SNARC-compatibility was manipulated. In the number parity task used by Gevers, Ratinckx and colleagues (2006), SNARC-compatibility was varied trial-by-trial, whereas in the number comparison task used in the present experiment, SNARC-compatibility was necessarily varied across blocks of trials. That the P300 amplitude was functionally meaningful in the present experiment is supported by the fact that P300 amplitudes were predictive of behavioral RTs.

Notably, the time interval in which the SNARC effect was detected for the P300 was largely overlapping with the intervals in which the SNARC effect was observed for the LRP (time-locked to D2). Qualitatively, changes in amplitude for the P300 across conditions appear to correspond with changes in amplitude for the pre-subtraction waveforms contributing to the LRPs. This suggests the possibility that amplitude for the pre-subtraction waveforms contributing to the LRPs may have been partly influenced by P300 amplitude (although the degree of ERP lateralization reflected in the post-subtraction LRP waveforms would have been independent of this influence). However,

there were no significant correlations between amplitudes for P300 and the pre-subtraction waveforms contributing to the LRPs, suggesting that this relationship is only qualitatively apparent in the group averages and did not hold at the individual level.

Nonetheless, the SNARC effect on P300 amplitude, and the scalp distributions for pre-subtraction ERPs contributing to the LRPs, might be taken as evidence for parietal contributions to the SNARC effect on response-selection (Hubbard et al., 2005). The P300 SNARC effect suggests moreover that there was "early communication" between response-selection and stimulus-evaluation processes, as in a "continuous flow" model of cognitive control (Coles et al., 1988). It might be conjectured from this evidence that a "mental load" was imposed on participants by maintaining in working memory a relatively counterintuitive stimulus-response mapping throughout the task, which was reflected as a weaker cortical response overall to the imperative stimulus D2 in SNARC-incompatible conditions.

Correlations between P300 Amplitudes and Behavioral RTs

To investigate whether P300 amplitudes were functionally meaningful, correlations with behavioral RTs were examined. Notably, P300 amplitudes when Prior Response-Probability was equal to 1 were correlated with behavioral RTs in some conditions. In SNARC-Compatible conditions higher P300 amplitudes predicted faster RTs when Prior Response-Probability was equal to 1 (SNARC-Incompatible), $r = -.427$, $p = .033$; and when Prior Response-Probability was equal to .66 and responses were invalidly cued (SNARC-Compatible), $r = -.412$, $p = .041$. In SNARC-Incompatible conditions higher P300 amplitudes predicted faster RTs when Prior Response Probability was equal to 1 (SNARC-Incompatible), $r = -.537$, $p = .006$; and when Prior Response-Probability was equal to .66 and responses were invalidly cued (SNARC-Compatible), $r = -.399$, $p = .048$.

Scatterplots depicting these significant correlations between P300 and RT variables are presented in Figure 23. No other significant relationships between P300

amplitudes and RTs were observed. Moreover, there were no significant relationships between LRP slopes and P300 amplitudes across conditions (*p*s > .05). Neither were there any significant correlations between amplitudes for P300 and for pre-subtraction ERPs contributing to LRPs in the overlapping time window (200 – 400 ms post-D2) in which the SNARC effect was significant for the LRP (*p*s > .05).

That P300 amplitudes were functionally meaningful is shown by significant correlations with behavioral RTs in some conditions. Higher P300 amplitudes were associated with faster RTs, suggesting that increased cortical response to imperative stimulus D2 was associated with faster stimulus evaluation and response-selection. Results suggest that maintaining a counterintuitive stimulus-response mapping in working memory imposed a "mental load" which reduced cortical activity devoted to processing the imperative stimulus D2 in SNARC-incompatible conditions, leading to slower decision making reflected as RTs.

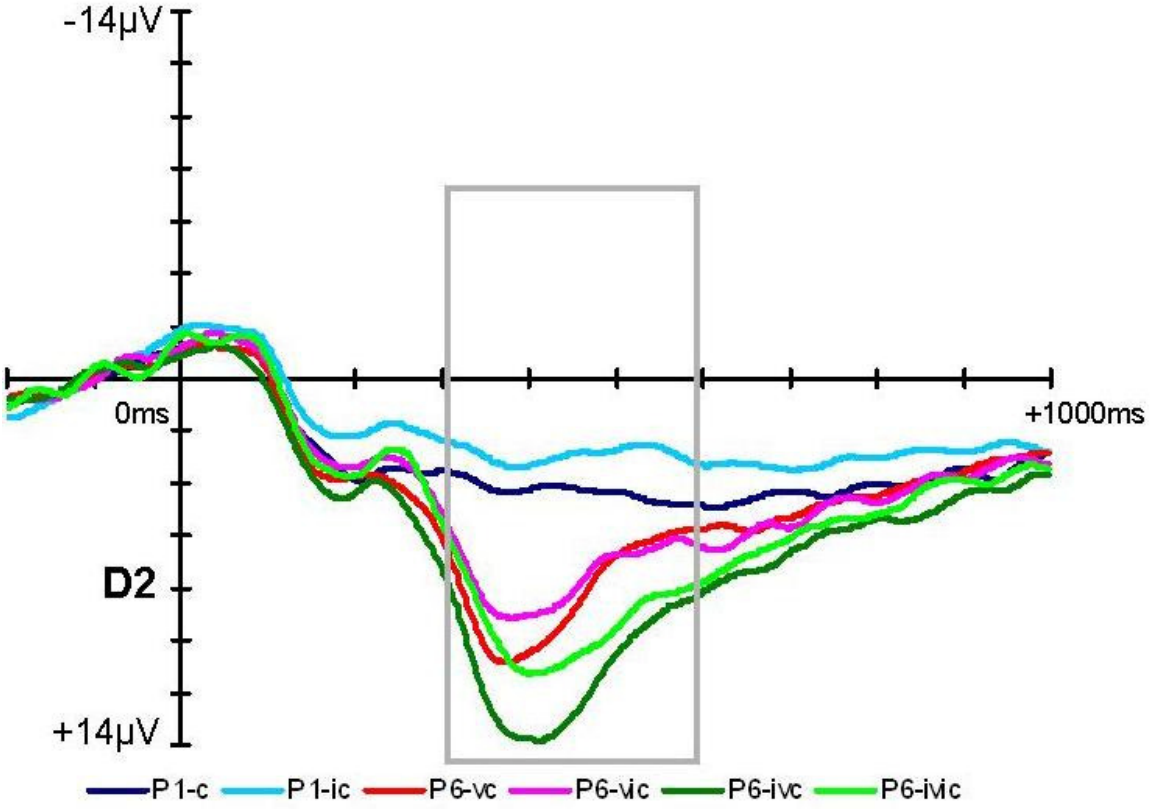

Figure 22. P300 ERP Time-Locked to D2. P300 ERP evoked by D2 stimulus at Pz electrode. Box indicates time window in which mean area amplitude was compared across conditions.

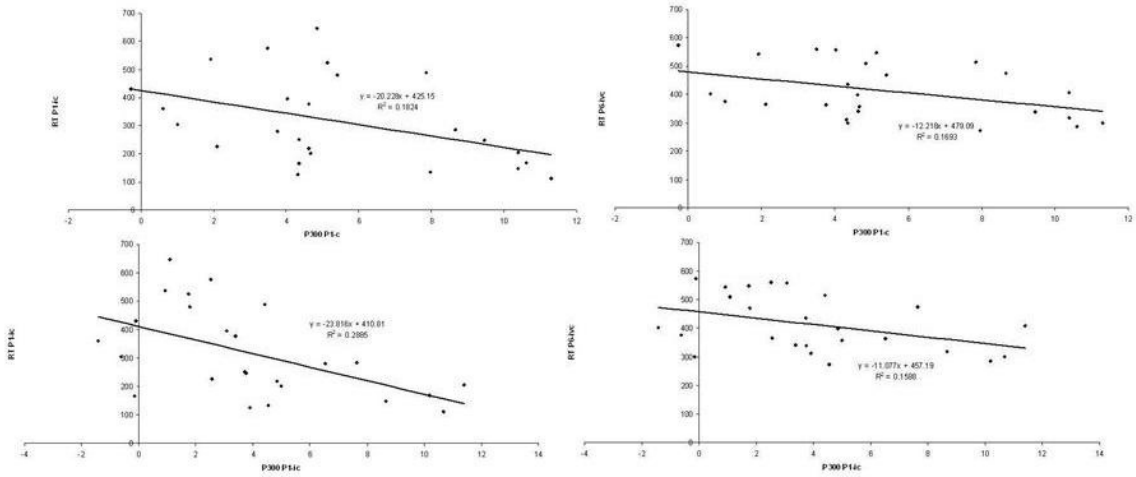

Figure 23. Scatterplots: P300 Amplitude Predicting RTs. P300 amplitude (x-axis) predicting RTs (y-axis). *Upper Left*: P300 amplitude Prior Response-Probability = 1 (SNARC-Compatible), predicting RTs Prior Response-Probability = 1 (SNARC-Incompatible). *Upper Right*: P300 amplitude Prior Response-Probability = 1 (SNARC-Compatible), predicting RTs Prior Response-Probability = .66 responses invalidly cued (SNARC-Compatible). *Lower Left*: P300 amplitude Prior Response-Probability = 1 (SNARC-Incompatible), predicting RTs Prior Response-Probability = 1 (SNARC-Incompatible). *Lower Right*: P300 amplitude Prior Response-Probability = 1 (SNARC-Incompatible), predicting RTs Prior Response-Probability = .66 responses invalidly cued (SNARC-Compatible).

Summary and Discussion ERP Results Experiment 1

In sum, the present LRP results are overall consistent with conclusions from the limited number of previous ERP studies of SNARC effects. Moreover, the present work generalizes from ERP investigations of SNARC in the number parity task to the number comparison task. Specifically, present results are in agreement with the conclusion that SNARC interference arises and is resolved during intermediate processing stages related to pre-motoric response-selection. However, the SNARC effect on the P300 in the present work diverges somewhat from the results of a previous experiment in which SNARC-compatibility was varied trial-by-trial (Gevers, Ratinckx et al., 2006), and in which no SNARC effect was observed for the P300. Thus, the present work also contributes a novel finding to the literature as well as confirmatory ones. The reduced P300 in SNARC-incompatible conditions is suggestive of a parietal source for the SNARC effect, and is provisionally interpreted here as reflecting a reduced cortical response to the imperative stimulus number when a counterintuitive stimulus-response mapping needed to be maintained in working memory over the course of performing the comparison task. In the following section, and existing theory of the SNARC effect, which can be applied to "conflict tasks" more generally, is modified and applied in a qualitative manner to give a possible account of the present behavioral and ERP findings.

Dual-Route Model of the SNARC Effect

In the dual-route model of the SNARC effect (Gevers, Ratinckx et al., 2006; Gevers, Verguts et al., 2006), possible responses are activated in parallel, and relevant as well as irrelevant information in favor of one response versus another is propagated through multiple pathways. This theory of the SNARC effect is derived from more general accounts of performing "conflict tasks" in which interference for response-selection is induced by dimensional overlap between a task-irrelevant stimulus dimension and a task-relevant response dimension (Kornblum et al., 1990), in which executive

control of cognition is required to over-ride bottom-up influences on behavior in order to accomplish task goals, such as in Stroop (Macleod, 1991) or flankers tasks (Eriksen & Eriksen, 1974).

In the computational model of the SNARC effect by Gevers, Verguts and colleagues (2006), the mental number line is represented by the joint activation of elements in a "number field" and a "standard field." The "number field" codes for specific the quantity information represented by the numerical stimulus and the "standard field" represents the mean of the range of presented numbers. When a numerical stimulus is presented in a comparison task, magnitude information is automatically coded coarsely into binary categories (small/large) by a "magnitude layer" receiving information from the "number field" and "standard field"—thus according to the spatially directed mental number line.

This information is transmitted to a "response layer" consisting of two spatially defined choices (left/right), via a fast, "unconditional" route. The left/right response nodes are connected through lateral inhibition. One response is chosen for execution when an activation threshold is reached for one option versus the other. The nodes in the response layer also receive task-specific activation via a slow, "conditional" route, which conveys information related to task instructions such as the stimulus-response mapping (e.g., "if 'small' respond 'left'" versus "if 'small' respond 'right'"). Thus these two routes can be seen to correspond roughly to distinctions made elsewhere between stimulus-driven and goal-driven orienting processes in theories of attentional control (Corbetta & Schulman, 2002).

When magnitude information, coded according to a spatially directed mental number line, is "congruent" with task instructions, information in the unconditional and conditional routes converge to the same response option and thus responses are speeded. This would occur when, for example, magnitude is "small" and task instructions say to respond "left" when magnitude is "small." When magnitude information is in conflict

with task instructions, information in unconditional and conditional routes do not converge on the same response option and thus responses are slowed. This would occur when, for example, magnitude is "small" and task instructions say to respond "right" when magnitude is "small."

It might be possible to adapt this framework to performance of the number comparison task in the present experiment, to account for why the SNARC effect on RTs was attenuated when response-cuing provided complete information about the upcoming D2/response, and for why SNARC effects were evident in ERPs only after the appearance the imperative stimulus D2. The model would be run in two cycles, first when the D1 response-cue appears, and again subsequently when the imperative stimulus D2 appears. Additionally, there would need to be some mechanism for representing "expectancy" in a graded manner, based on a more exact magnitude representation of the D1 response-cue. Based on activation of the number field and the standard field, the model could be adapted to represent magnitude in a way that differentiates "very small" from "small" and "very big" from "big" so that expectancy could be differentiated according to "certainty" versus "likelihood." Response activation associated with certainty would be allowed to grow more quickly than that associated with likelihood. Furthermore, there would need to be a mechanism for suppressing activation in the D1-D2 interval to prevent premature responses.

First, consider the case where D1 = 1 and D2 = 9 and instructions are SNARC-compatible (1, 9, C). The first cycle is initiated upon presentation of D1. The appearance of D1 would activate a magnitude representation of "small" which would activate the left-hand response automatically. But the magnitude information in D1 would also be available to an "expectancy layer" which activates a representation of the conditional statement "if D1 is (very) small, expect D2 to be big (with certainty)." This would be coupled to the "conditional route" representing task instructions, "if D2 big, press right." This would activate the right-hand response, but more slowly. So far the fast

unconditional route would be activating a left-hand response and the slow conditional route would be activating a right-hand response.

However, there is another task instruction that says "do not respond before seeing D2." Thus the fast activation of the left-hand response by magnitude of D1 would need to be suppressed in order to prevent premature responses. There is evidence for inhibitory processes that are engaged to prevent premature responding (e.g., Duque, Lew, Mazzocchio, Olivier & Ivry, 2010). In contrast, the activation of the right-hand response through the conditional route would not need to be suppressed because it would grow slowly and would not reach threshold before the appearance of D2, and thus would not come into conflict with the instruction forbidding early responses.

The second cycle is initiated upon presentation of D2. Upon appearance of D2, activation in favor of a right-hand response would quickly reach threshold. Magnitude representation of D2 would be "big," activating a right-hand response via the unconditional route of Cycle 2. Furthermore, activation in favor of a right-hand response from the conditional route that started in Cycle 1 would have been growing in the meantime. Additionally, activation via the conditional route of Cycle 2 would be toward the right-hand response ("if D2 big, press right"). Thus, all active routes at this point in time would be converging on a right-hand response.

Now consider the same D1-D2 pair but in the SNARC-incompatible condition (1, 9, IC). Cycle 1: D1 magnitude would send activation to the left-hand response via the fast unconditional route. Expectancy/task instructions would activate a left-hand response as well (If D1 small, expect D2 big; if D2 big press left) via the slow conditional route. The instruction not to respond before D2 would suppress the fast activation of the left-hand response, but not the slow activation of the left-hand response. Cycle 2: D2 appears, automatically priming a right-hand response via the fast unconditional route. But activation of the left-hand response has been allowed to grow in the meantime, and thus would have a "head start" on the unconditional right-hand activation. Furthermore,

the slow conditional route from Cycle 2 would activate a left-hand response. Thus, activation from two sources would be converging in favor of a left-hand response, and information from one source would be in favor of a right-hand response. Of the two routes supporting a left-hand response, one would have been increasing in activation from Cycle 1, and would thus be in a position to win the race to response threshold. Therefore, there would be an attenuated SNARC effect on RTs when D1 supported complete certainty regarding the upcoming D2/response.

Next, consider the case where D1 = 3 and D2 = 9 and instructions are SNARC-compatible (3, 9, C). Cycle 1: The appearance of D1 would activate a magnitude representation of "small" which would activate the left-hand response automatically. This activation would be suppressed to prevent premature responses. The slower conditional route information would activate the right-hand response, (If D2 is small, but not very small, expect D2 big, with likelihood. And if D2 is big, respond right). This activation would grow even more slowly in the case of mere likelihood compared to certainty, and thus would not be suppressed during Cycle 1. Cycle 2: The appearance of D2 would automatically activate the right-hand response. This would converge with activation in favor of right-hand response that was allowed to continue from Cycle 1. Additionally, conditional route information in Cycle 2 would support a right-hand response. Thus, all three sources of activation would be converging on a right-hand response.

Next, consider the case where D1 = 3 and D2 = 9 and instructions are SNARC-Incompatible (3, 9, IC). Cycle 1: The appearance of D1 would activate a magnitude representation of "small" which would activate the left-hand response automatically. This would be suppressed by the instruction against premature responses. But here in the SNARC-incompatible case, the slower conditional route information would also activate the left-hand response (If D2 is small, but not very small, expect D2 big, with mere likelihood. And if D2 is big, respond left). It can be assumed that this activation would

grow even more slowly in the case of mere likelihood compared to certainty, and thus would not be suppressed during Cycle 1. Cycle 2: The appearance of D2 would activate a right-hand response via the unconditional route. Conditional route information from Cycle 1 would have been growing to support a left-hand response. Conditional information from Cycle 2 would support a left-hand response. Thus, two out of three sources of activation would converge to support a left-hand response, and these would be the slower routes. The faster activation of the right-hand response from the unconditional route in Cycle 2 would compete with the slower activation from the conditional routes activated in Cycles 1 and 2. Thus there would be a SNARC effect on RTs when the D1 response cue provided only likelihood information and not certainty.

Next, consider the case where responses are invalidly cued by D1, for example when D1 = 3 and D2 = 1, and instructions are SNARC-compatible (3, 1, C). Cycle 1: activation in favor of a left-hand response has been suppressed in the unconditional route to prevent premature responses but activation in favor of a right-hand response is allowed to grow in the conditional route. Cycle 2: unconditional route fast activation supports left-hand response, conditional route slower activation also supports left-hand response. Only two out of three sources of activation support the correct left-hand response, but one is relatively fast.

Finally consider the case where D1 = 3 and D2 = 1 and instructions are SNARC-Incompatible (3, 1, IC). Cycle 1: fast unconditional route activation left-hand response suppressed, slow conditional route activation left-hand response allowed to grow. Cycle 2: fast unconditional route left-hand activation but slow conditional route activation for right-hand response. Thus, two out of three support the incorrect left-hand response. Furthermore one is relatively fast and the other has been allowed to grow since Cycle 1. Thus there is stronger activation of the incorrect response in the case where response-cuing provides only likelihood information and stimulus-response mapping is SNARC-

incompatible compared to when it is SNARC-compatible. Therefore, correct responses will be slower in the SNARC-incompatible versus SNARC-compatible condition.

To summarize, the preceding discussion was a qualitative stepping-through of the dual-route model of the SNARC effect, adapted here by additional mechanisms for computing expectancy and for suppressing premature responses. This exercise of stepping through the conditions in the experiment with the modified dual-route model led to conclusions that were consistent with the RT results, namely, a SNARC effect when prior response-probability was equal to .66 but not when it was equal to 1; and a SNARC effect for invalidly cued trials.

The dual-route model is a cognitive theory and does not make biological/psychophysiological assumptions or predictions. However, the qualitative two-cycle dual-route framework presented above is broadly consistent with the ERP results of the present experiment, to the extent that that SNARC interference was evident in the LRP (and P300) components after the appearance of the imperative stimulus D2 but not before, i.e., during "Cycle 2" but not "Cycle 1" of the adapted model. In the above framework, this would be a consequence of the mechanism for suppressing fast unconditional-route activation of a spatial dimension associated with the D1 response-cue, in order to prevent premature responses.

Future Directions

It may be profitable in future research to more rigorously explore the implications of the two-cycle dual-route framework articulated in the preceding remarks. In general, quantitative theories are relatively rare in electrophysiological research. As a direction for future research more generally, it may be profitable for electrophysiology as a field to promote the development and refinement of quantitative theories integrating cognitive and psychophysiological concepts (Jennings & van der Molen, 2006).

One of the key findings of the experiment was that SNARC effects were observed in the LRP after the appearance of the second number for comparison but not before,

even when the first number had given complete advance information to enable earlier response-selection. This was explained by appealing to a mechanism for suppressing activation that could lead to premature responses. This hypothesis should be a focus of future experiments.

The experiment produced a novel finding of a SNARC effect on the P300 ERP component, in which amplitudes were more positive in SNARC-compatible conditions. This result is suggestive of parietal contributions to the SNARC effect, and should be a focus of future experiments. For example, it may be due to an artifact of the design, in which SNARC-compatibility was varied across blocks of trials rather than trial by trial. Future experiments would need to address this issue by manipulating SNARC-compatibility trial by trial, while preserving the response-cuing device. It would be further beneficial to disentangle potential SNARC interference associated with the response cue from prior response-probability, by communicating prior response-probability with a response cue that does not itself carry numerical magnitude information., or alternatively, manipulating prior response-probability by means of varying stimulus frequencies across blocks of trials.

Additional directions for future research include investigating whether present SNARC effects are specific to numerical stimuli or if they would be obtained with other kinds of ordinal information such as letters, days of the week, or months, etc. Further, it would be valuable to explore different stimulus-response mappings, for example, with vertically arranged response buttons, to determine if the relevant spatial coordinates refer to the spatial location of the hands or the response buttons.

CHAPTER 4

SPATIAL-NUMERIC ASSOCIATION OF ATTENTIONAL CUING

ERP studies of SNARC in the parity task have observed ERP effects associated with response-selection processes as a function of SNARC-compatibility; but effects of a mental number line concept are possible at earlier stages of processing as well. The goal of Experiment 2 was to extend the previous investigation of SNARC with respect to "response-space" to the domain of visuospatial attention. A small amount of previous work has addressed the possibility that numerical magnitude can influence earlier stages of processing such as orienting visuospatial attention, as a spatial-numeric association of attentional cuing (SNAAC).

SNAAC

Results suggest that digits can activate an implicit generalized code for magnitude that can bias attention during the cue-target interval, in a similar way to explicitly spatial pre-cues such as arrows or peripheral flashes (e.g., Posner, 1980). Fischer, Castel, Dodd, and Pratt (2003) examined the effect of digit-magnitude on orienting visuospatial attention, presenting a single digit at fixation to serve as a "warning signal" in a target detection task. Simple RTs to detect a peripheral target in the left visual field were faster after viewing small-magnitude digit pre-cues ("validly-cued") than after viewing large-magnitude digit pre-cues ("invalidly-cued") presented at fixation. Corresponding effects were observed for RTs to detect targets in the right visual field. These effects were interpreted as attentional orienting in a manner consistent with the ordered mental number line. This phenomenon can be alternatively called "attentional-SNARC" (Dodd, Van der Stigchel, Leghari, Fung & Kingstone, 2008).

An open question is whether digit stimuli elicit exogenous (automatic) shifts of attention, like a bright bar suddenly flashed in a possible target location prior to the appearance of the target; or else whether they facilitate endogenous (voluntary) shifts like an arrow, or other symbol, associated with one side of space or the other. Exogenous, or automatic, attentional orienting occurs in response to an attention-capturing stimulus like a briefly flashed bar in one visual hemifield before a target appears near that location. Endogenous, or voluntary, attentional orienting is mediated by interpreting a symbolic cue like an arrow symbol or other figure that can be assigned to direction in left-right space (Wright & Ward, 2008; but for an alternative taxonomy see Gibson & Kingstone, 2006).

The assumption that digit magnitudes are processed automatically and obligatorily is widely held, but has been sometimes challenged (e.g., Pansky & Algom, 2002). Notably in this connection, Galfano, Rusconi, and Umiltà (2006) replicated, and then reversed, the original findings of Fischer et al. (2003), by manipulating explicit instructions to participants concerning how to interpret digit stimuli according to a directed mental number line. In one condition, cuing instructions were consistent with the proposed dominant tendency to associate small numbers with left visual space and large numbers with right visual space. In the other condition, space-number mappings were reversed by the instructions.

RTs showed similar benefits to "validly-cued" targets across instructional settings, suggesting that attentional effects due to digit magnitude are not automatic or obligatory, but are to some extent susceptible to voluntary and intentional control. In contrast, the attention-directing properties of more biologically significant orienting cues

such as eye-gaze cartoons were less modifiable by task instructions (Galfano et al., 2006). Thus, it appears that digit magnitude can be used to direct attention to spatial locations in accordance with a directed mental number line, but that the mapping of digit-magnitude to space is not fixed in a left-right orientation and can be altered flexibly according to participant intentions.

The attentional orienting properties of digit pre-cues are ambiguous in light of the evidence. Because digit pre-cue magnitude was unrelated to subsequent target-location, and because participants were instructed as much, results of Fischer and colleagues (2003) suggested that exogenous orienting mechanisms were at work. However, results of Galfano and colleagues (2006) showed that the orienting properties of digit pre-cues were easily modifiable by task instructions and participant goals. Together, these considerations suggest that digit cues are uneasily accommodated by the general exogenous/endogenous framework for interpreting the attention-directing properties of pre-cues (see also Gibson & Kingstone, 2006). The following section introduces some recent ERP experiments that might further clarify the attention-directing properties of digit pre-cues.

Experiments with Simple Target Detection and ERP

Salillas, El Yagoubi, and Semenza (2008) performed a straightforward ERP replication of the behavioral experiment by Fischer et al (2003). Note that here as in the study by Fischer and colleagues (2003), "cue validity" was defined on the basis of the hypothesized SNARC relationship. Participants were instructed to ignore digit stimuli. The authors reported SNARC-like attentional effects from central digit stimuli in ERP responses to targets as early as 80 ms after stimulus onset. Peak amplitudes for the P1

component for left visual field targets following small-magnitude digit stimuli (valid left-cue) were greater than following large-magnitude digit stimuli (invalid left-cue). Conversely, P1 amplitudes for right visual field targets were greater following large-magnitude digit stimuli (valid right-cue) than following small-magnitude digit stimuli (invalid right-cue). Finding increased P1 amplitude in response to target stimuli as a function of valid pre-cuing is usually interpreted to indicate enhanced stimulus processing due to attention (Luck, Woodman & Vogel, 2000). Thus, results suggest that centrally viewed digits can direct attention to peripheral spatial locations, with consequences for subsequent stimulus processing, similar to more traditional orienting cues like arrows or flashes (Posner, 1980; Wright & Ward, 2008).

Ranzini, Dehaene, Piazza, and Hubbard (2009) extended the work of Salillas and colleagues (2008) by examining ERPs to the digit pre-cues instead of the subsequent targets. Ranzini and colleagues (2009) examined ERP responses to digit pre-cues compared to arrows, again in a target detection task requiring speeded simple RTs. As in the study by Salillas and colleagues (2008), orienting cues were not systematically related to the location of subsequent targets, as is usual in studies of "exogenous" orienting cues. Indeed, participants were explicitly instructed that arrow-direction and digit-magnitude were both unrelated to subsequent target location.

Nevertheless, Ranzini and colleagues (2009) found that arrow and digit stimuli alike led to faster RTs when arrows or digit pre-cues validly directed attention to the location at which subsequent targets in fact appeared. Furthermore, arrow and digit pre-cues alike elicited ERPs that were lateralized systematically with the presumed direction of attention, corresponding to two lateralized ERP components referred to as the Anterior

Directing Attention Negativity and Early Directing Attention Negativity (EDAN) components; which can be observed during the cue-target interval in attentional cuing studies (Jongen, Smulders & Van der Heiden, 2007). However, attentional ERP effects were much smaller for digit pre-cues compared to arrows.

Overall, these findings further demonstrated that digit stimuli can elicit lateralized shifts of attention consistent with an underlying spatial representation of numerical magnitude. Additionally, because arrow and digit stimuli were non-predictive of subsequent target locations, and because participants were explicitly instructed as much, these findings suggest that digit stimuli may operate via exogenous cuing mechanisms during the cue-target interval (and similar to arrows; see also Gibson & Kingstone, 2006).

Theoretical Accounts of SNAAC

Behavioral and ERP investigators of the orienting properties of digits have interpreted their findings as evidence for automatic responses to digit magnitude, in a manner corresponding to a spatial organization of numerical concepts (a directed mental number line), according to which relatively small-magnitude numbers are associated with left visual space and relatively large-magnitude numbers are associated with right visual space. Regardless of the precise nature of the underlying mechanisms, these previous studies have shown that digit pre-cue magnitude can be used to elicit shifts of visuospatial attention in advance of an expected imperative stimulus, indicated by RTs and ERPs.

Present Research (Experiment 2)

The goal of Experiment 2 was to extend the investigation of spatial-numeric associations in relation to response-selection that was pursued in Experiment 1, to

investigate spatial-numeric associations in relation to attentional cuing, by presenting task-irrelevant visual probes during D1-D2 interval, either to the left or right of fixation. ERP responses to these task-irrelevant visual probes were expected to be modulated by D1 magnitude corresponding to a directed mental number line, as in the target detection experiments with digit pre-cues, reviewed in the introduction (Ranzini et al., 2009; Salillas et al., 2008). It was predicted that ERPs to left-side visual probes would be enhanced following small- versus large-magnitude digit pre-cues, and that ERPs to right-side visual probes would be enhanced following large- versus small-magnitude digit pre-cues. More specifically, these effects were expected for early visual ERPs such as the P1 or N1 components, usually occurring 100 ms – 200 ms post-stimulus, and have been shown to be enhanced by attention (Luck et al., 2000).

CHAPTER 5

METHOD EXPERIMENT 2

This chapter reports information about participants, materials and procedure, for behavioral tasks and electrophysiological recording in Experiment 2.

Participants

28 volunteers (14 females) between the ages of 18 and 40 years (M = 19.71, SD = 1.90) participated in the experiment and were compensated with pay or partial course credit. All participants had normal or corrected-to-normal vision. 27 participants were right-handed by self-report. The experiment was done with the approval of the Institutional Review Board of Georgia Institute of Technology. Participants gave written informed consent.

Procedure

Trial sequences and stimuli are depicted in Figure 24. The experimental tasks were exactly as in Experiment 1 except for the following differences. A task-irrelevant visual probe was presented during the D1-D2 interval, either to the left or right of fixation, with equal likelihood on each trial, with the constraint that probes appeared to the left or right an equal number of times in each block for each D1 cue. Probes appeared during the D1-D2 interval either relatively early (200 ms) or late (450 ms) after D1 onset (an equal number of times per block). The specific stimulus-onset asynchronies (200 ms versus 450 ms) were chosen based on extensive past research showing these to be the

time ranges in which, respectively, exogenous and endogenous attentional cuing benefits can be maximally distinguished (Wright & Ward, 2008). Additionally, 450 ms was chosen to match the stimulus-onset asynchrony in the target detection experiment by Salillas and colleagues (2008). The probe stimulus was a '+' symbol displayed approximately 1 cm in height by 1 cm in width, subtending approximately 1º of visual angle, in white font against the black background, approximately 4º of visual angle to the left or right of fixation. Participants were instructed to ignore the task-irrelevant visual probes. Probes did not appear on 1/3 of trials (no-probe trials). D1 cues '1' and '3' were classified as "small" and D1 cues '7' and '9' were classified as "big." There were a total of 48 trials in the experiment for each cell of the design, crossing the factors D1 magnitude (small, big), hemifield in which the probe appeared (left, right), and time at which the probe appeared (early, late).

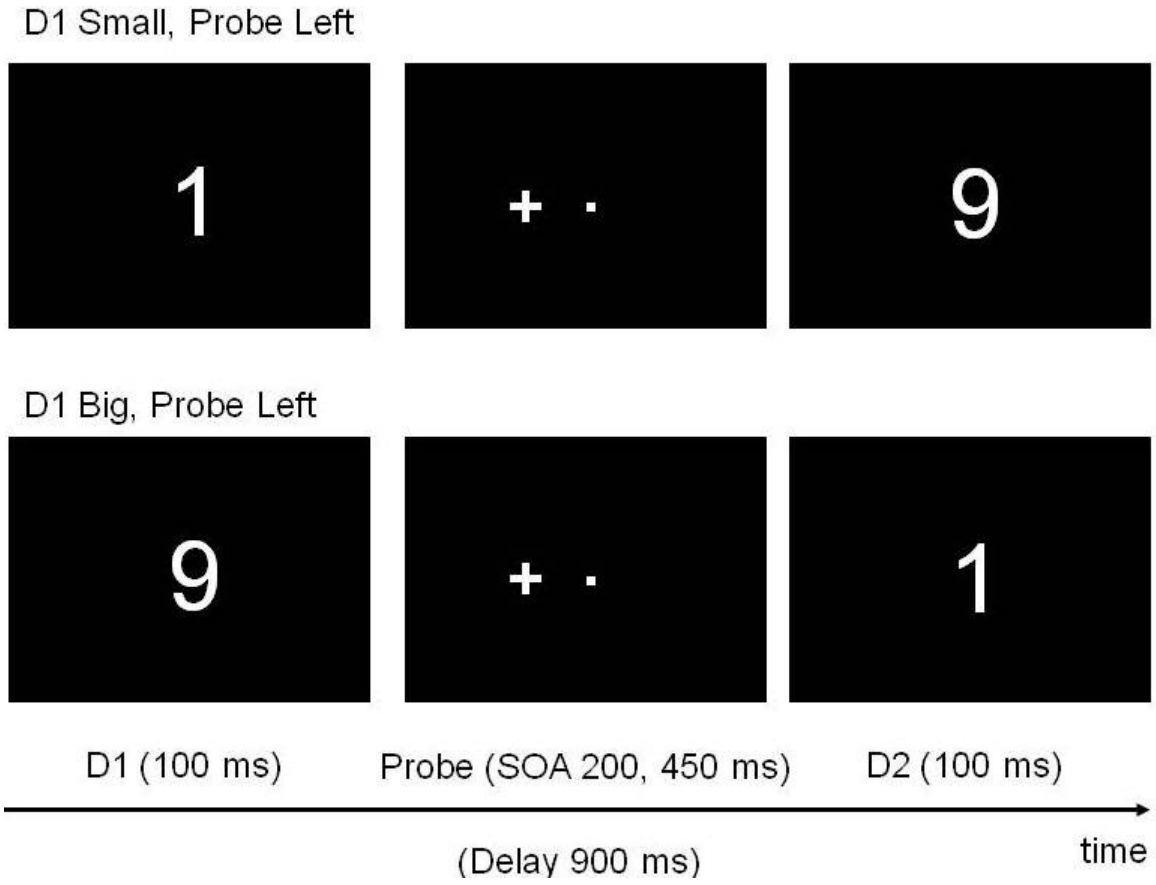

Figure 24. Trial Sequence Experiment 2. Event-sequence and stimuli in Experiment 2 trials. Participants reported whether the second digit (D2) was less than or greater than the first digit (D1) by responding with left- or right-handed key-press. Participants were instructed to ignore task-irrelevant peripheral probes, here depicted as appearing to the left of fixation.

EEG Recording and Analysis

Electrophysiological data were recorded using a BioSemi Active-Two amplifier system (Amsterdam, Netherlands) and was digitized at 512 Hz. Scalp potentials were recorded from 32 electrode sites: FP1/2, F7/8, F3/4, Fz, C3/4, Cz, P7/8, P3/4, Pz, T7/8, O1/2, Oz, AF3/4, FC1/2, CP1/2, PO3/4, FC5/6, and CP5/6. Two additional electrodes will serve as reference and ground electrodes. These electrodes were the common mode sense (CMS) and driven right leg (DRL), respectively. Vertical electrooculogram (EOG) was calculated offline as the difference between electrodes positioned above and below the left eye. Horizontal EOG was calculated offline as the difference between electrodes positioned on the outer canthi of the left and right eyes.

EEG data were analyzed using BrainVision Analyzer (Brain Products, Gilching, Germany). Offline, all channels were re-referenced to the algebraic average of the left and right mastoids. Continuous EEG was digitally band-pass filtered from 0.1 to 30 Hz using a zero phase-shift Butterworth filter (12 dB/oct). These procedures were as in Experiment 1 except for the following differences. EEG were segmented into 700 ms segments beginning 200 ms pre-stimulus and continuing 500 ms post-stimulus (the peripheral probe). Segments were then baseline corrected by setting the average of the 200 ms pre-stimulus baseline to zero.

The ocular correction method was not used in Experiment 2 for removing ocular artifacts. Instead, a two-step procedure was used in Experiment 2 to exclude artifacts due to eye-movements: 1) first, activity greater than ± 50 μV in the HEOG channel was rejected as artifacts, and 2) next, participants' averages were formed for right and left visual field probes separately and participants were excluded if average HEOG activity

exceeded ± 5 μV. This ensured that no systematic eye-movements over 0.2º were included in the data. Additionally, segments containing activity greater than ±80 μV in the scalp and VEOG channels were considered artifacts and rejected in order to control for eye blinks.

CHAPTER 6

RESULTS AND DISCUSSION EXPERIMENT 2

In this chapter behavioral results of Experiment 2 are reported first, examining combined effects of SNARC-compatibility and prior response-probability; and separately, examining combined effects of SNARC-compatibility and cue-validity. Then electrophysiological results are reported, examining effects of D1 magnitude, visual field in which the task-irrelevant probe appeared, and the time at which it appeared.

Behavioral Results

Behavioral results in Experiment 2 were examined to check for replication of effects in Experiment 1. However, the main focus of the investigation in Experiment 2 was on the ERPs to the task-irrelevant peripheral probes.

As noted, the nesting of "D1 response-cue-validity" within the manipulation of prior response-probability entailed that separate analyses were required to examine effects of SNARC-compatibility in combination with those of 1) prior response-probability and 2) D1 response-cue-validity. These are reported next in turn, with separate ANOVAs for response time (RT) and response accuracy.

SNARC-Compatibility and Prior Response-Probability

A 2 x 2 repeated-measures ANOVA was conducted to examine effects of the independent variables SNARC-Compatibility (Compatible, Incompatible) and Prior Response-Probability (.66, 1) on Mean RT as the dependent variable. Only correct trials were included. Only trials in which D1 was a valid cue were included. Results across

conditions are depicted in Figure 25 (left panel). The effects of SNARC-compatibility and Prior Response-Probability were each significant, F (1, 27) = 12.84, p =.001, η_p^2 = .322, and F (1, 27) = 96.05, p < .001, η_p^2 = .781, respectively. RTs were faster in SNARC-Compatible versus SNARC-Incompatible conditions (M = 403.96, SE = 25.69, and M = 479.15, SE = 30.51, respectively). RTs were faster when Prior Response-Probability was equal to 1 versus when it was equal to .66 (M = 370.27, SE = 29.37, and M = 512.85, SE = 24.78, respectively). However, these effects were qualified by their significant interaction, F (1, 27) = 6.52, p = .017, η_p^2 = .194. Post hoc analysis confirmed that the effect of SNARC-Compatibility was larger when Prior Response-Probability was equal to .66 compared to when it was equal to 1 (M = 95.76, SE = 23.21, and M = 54.62, SE = 21.72, respectively), t (27) = 2.55, p = .017 (M_d = 41.14, SE_d = 16.12).

A 2 x 2 repeated-measures ANOVA was conducted to examine effects of the independent variables SNARC-Compatibility (Compatible, Incompatible) and Prior Response-Probability (.66, 1) on Mean Proportion-Correct Responses as the dependent variable. Only trials in which D1 was a valid cue were included. Results across conditions are depicted in Figure 25 (right panel). The effects of SNARC-Compatibility and Prior Response-Probability were not significant, F (1, 27) = 1.21, p = .280, η_p^2 = .043, and F (1, 27) = 1.07, p = .310, η_p^2 = .038, respectively. The interaction was not significant, F < 1.

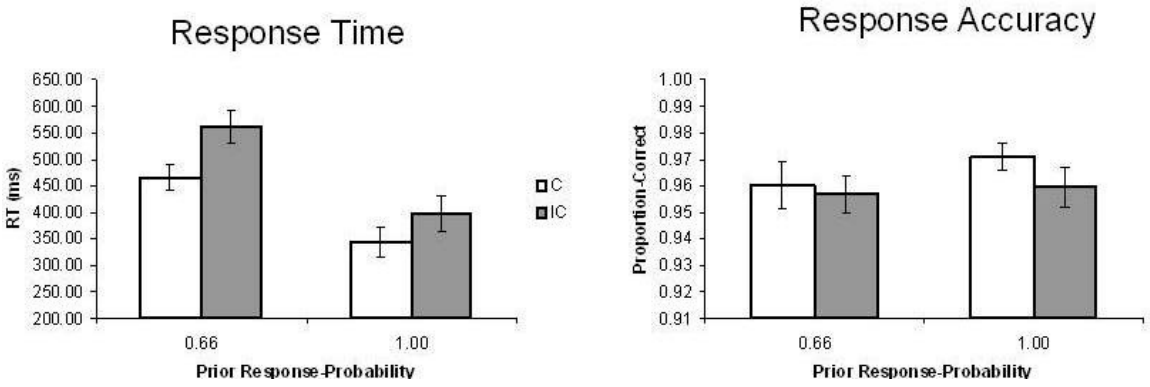

Figure 25. Behavioral Results SNARC and Prior-Response Probability. Response time (left) and response accuracy (right) in Experiment 2, with the factors of SNARC-compatibility and prior response-probability. Legend: *C* means SNARC-compatible, *IC* means SNARC-incompatible.

SNARC-Compatibility and Response Cue-Validity

Separately, a 2 x 2 repeated-measures ANOVA was conducted to examine effects of the independent variables SNARC-Compatibility (Compatible, Incompatible) and Cue-Validity (Valid, Invalid) on Mean RT as the dependent variable. Only correct trials were included. Only trials in which Prior Response-Probability was equal to .66 were included. Results across conditions are depicted in Figure 26 (left panel). The effects of SNARC-Compatibility and Cue-Validity were each significant, F (1, 27) = 20.75, p <.001, η_p^2 = .435, and F (1, 27) = 11.47, p = .002, η_p^2 = .298, respectively. RTs were faster in SNARC-Compatible versus SNARC-Incompatible conditions (M = 472.71, SE = 25.10, and M = 573.66, SE = 29.99, respectively). RTs were faster when the response was validly cued by D1 (M = 512.85, SE = 24.78, and M = 533.52, SE = 26.50, respectively). The interaction was not significant, F (1, 27) = 1.34, p = .257, η_p^2 = .047.

Separately, a 2 x 2 repeated-measures ANOVA was conducted to examine effects of the independent variables SNARC-Compatibility (Compatible, Incompatible) and Cue-Validity (Valid, Invalid) on Mean Proportion-Correct Responses as the dependent variable. Only trials in which Prior Response-Probability was equal to .66 were included. Results across conditions are depicted in Figure 26 (right panel). The effects of SNARC-Compatibility and Cue-Validity were not significant, F < 1, and F (1, 27) = 2.30, p = .141, η_p^2 = .078, respectively. The interaction was not significant, F (1, 27) = 1.15, p = .231, η_p^2 = .053.

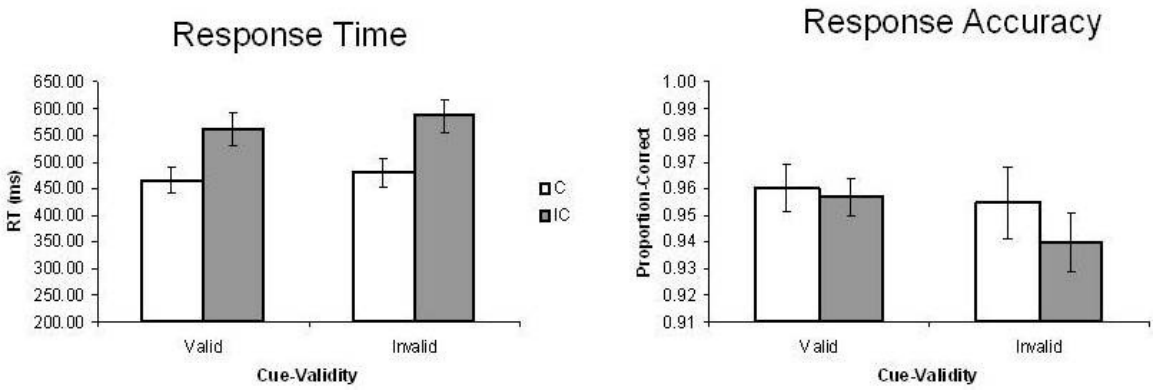

Figure 26. Behavioral Results SNARC and Response-Cue-Validity. Response time (left) and response accuracy (right) in Experiment 2, with the factors of SNARC-compatibility and prior response-probability. Legend: *C* means SNARC-compatible, *IC* means SNARC-incompatible.

Discussion Behavioral Results Experiment 2

RTs in the number comparison task largely replicated results of Experiment 1. This suggests that the additional experimental procedure of presenting task-irrelevant peripheral probes did not substantially change performance of the number comparison task (consistent with design intentions). As in Experiment 1, response accuracy did not provide evidence of speed-accuracy tradeoffs.

ERP Results

As noted, the main focus of the investigation in Experiment 2 was on the ERPs to the task-irrelevant peripheral probes. Therefore the experimental factors of SNARC-compatibility and prior response-probability do not contribute to the following analyses. ERPs at the contralateral posterior electrode (P8 and P7 electrodes, respectively) were submitted to analyses and are depicted time-locked to probes appearing in left and right visual hemifields, for either "early" (Figure 27) or "late" (Figure 28) probes. For improved visualization, high-frequency noise was additionally removed from the data before graphing, using a low-pass filter set at 10 Hz.

ERPs to Early probes (200 ms post-D1 onset) appeared to be distorted by ERPs to the preceding D1 cue, evident as drifting baseline activity. However, ERPs to Late probes (450 ms post-D1 onset) appeared more typical, showing clear negative peaks in the 100 – 200 ms post-probe interval, possibly corresponding to the visual N1 component, which is sensitive to attention (Luck et al., 2000). The following analyses of ERP mean area amplitude were focused on this time window.

ERP to Probe

2 x 2 repeated-measures ANOVAs were performed separately for probes appearing 200 ms and 450 ms after D1, with the factors Visual Hemifield (Left, Right) and D1 Magnitude (Small, Large) on mean area amplitude (μV) in the 100 – 200 ms post-probe interval, at the contralateral electrode. D1 pre-cues '1' and '3' were classified as "small" and D1 pre-cues '7' and '9' were classified as "large" for the following analyses. ERPs to left-side and right-side probes were analyzed at the respective contralateral posterior electrode, P8 and P7. Data from one participant were excluded due to excessive eye blinks.

Early Probe (200 ms Post-D2)

See Figure 27 for ERP waveforms. Mean area amplitude (μV) in the 100 – 200 ms post-probe interval was examined in ANOVA. The main effect of Visual Hemifield was not significant, $F < 1$. The main effect of D1 Magnitude was not significant, $F(1, 26) = 2.64$, $p = .116$, $\eta_p^2 = .092$. The interaction was also not significant, $F < 1$.

These data were re-examined after applying a .5 Hz high-pass filter, in order to remove potential distortion from low-frequency drift in the baseline period, but results were not substantially altered. ERPs in this analysis are further limited by the small number of trials contributing to the waveforms (maximum 48 per individual).

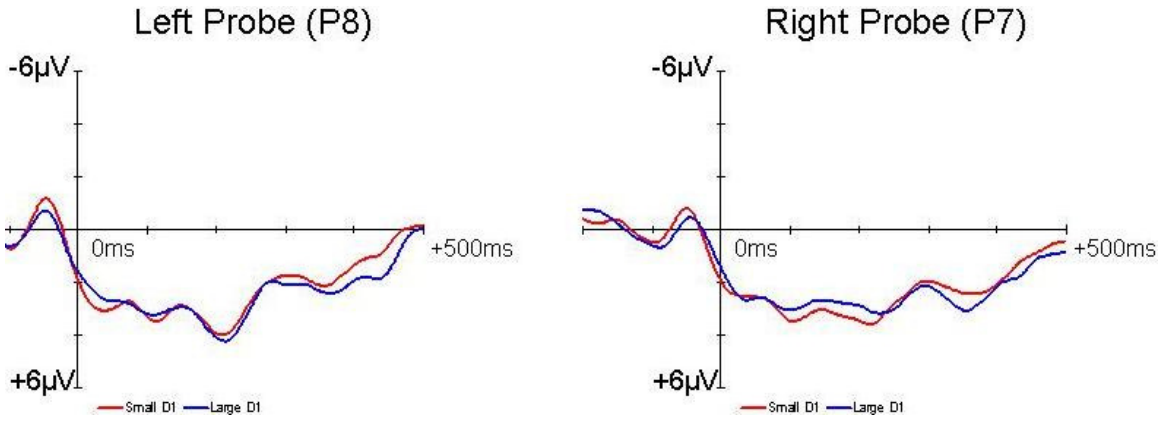

Figure 27. ERP to Early Probes. ERPs to early probes (200 ms post-D1 onset). Probe onset = 0 ms, unit = 100 ms. *P8* and *P7* indicate electrode.

Late Probe (450 ms Post-D2)

See Figure 28 for ERP waveforms. ERPs to Late probes (450 ms post-D1 onset) showed more typical-looking waveforms; with evident peaks around 100 – 200 ms post-probe. Mean area amplitude (μV) in the 100 – 200 ms post-probe interval was examined in ANOVA. The main effect of Visual Hemifield was not significant, F (1, 26) = 1.62, p = .214, η_p^2 = .059. The main effect of D1 Magnitude was not significant, F (1, 26) = 3.61, p = .068, η_p^2 = .122. The interaction was also not significant, $F < 1$.

However, these waveforms too seem to be distorted by some artifact, noting that they show a general drift as well as apparent separation of the waveforms at time-point zero (although this is not a statistically significant separation). ERPs in this analysis are further limited by the small number of trials contributing to the waveforms (maximum 48 per individual). These data were re-examined as well after applying a .5 Hz high-pass filter, in order to remove potential distortion from low-frequency drift, but the apparent separation at time-point zero was not substantially altered. It cannot be stated with confidence that the trend for an effect of D1 magnitude is specific to the N1 component.

Scalp maps for three time intervals are presented in Figure 29, Figure 30, and Figure 31. These suggest that the peak negativities in the time window 100 – 200 ms post-probe were specific to posterior electrodes contralateral to the visual hemifield in which the probe appeared. This would be consistent with the scalp distribution for the N1. In contrast, the scalp distributions corresponding to the earlier time window (0 – 100 ms post-probe) in which the waveforms appeared to separate do not show such regional specificity; neither do those for the subsequent time window (200 – 300 ms post-probe).

Therefore, the negative peaks occurring in the waveforms for late probe ERPs appear to be specific to visual processing of the peripheral probes.

But overall, the ERPs to the late probes may not be sufficiently credible to evaluate the research hypothesis, much like the ERPs to the early probes. The simplest explanation for this state of affairs is related to the fact that a maximum of only 48 trials per individual could have contributed to the ERPs for each cell of the design, which includes early and late probes as a within-subjects factor. This is likely an insufficient number of trials for an adequate signal-to-noise ratio for examining relatively small ERP components such as P1 or N1 (Luck, 2005b). This design limitation would need to be remedied in future investigations of the attention-directing properties of numerical stimuli.

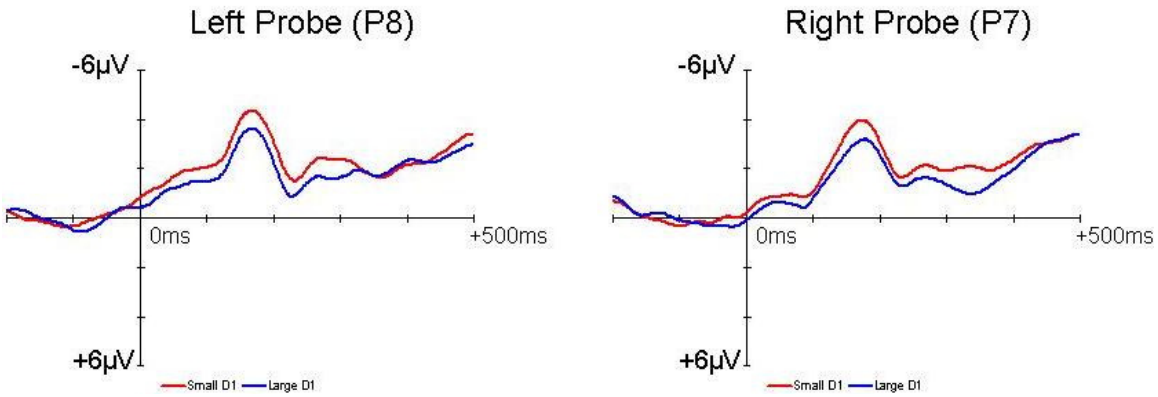

Figure 28. ERP to Late Probes. ERPs to late probes (450 ms post-D1 onset). Probe onset = 0 ms, unit = 100 ms. *P8* and *P7* indicate electrode.

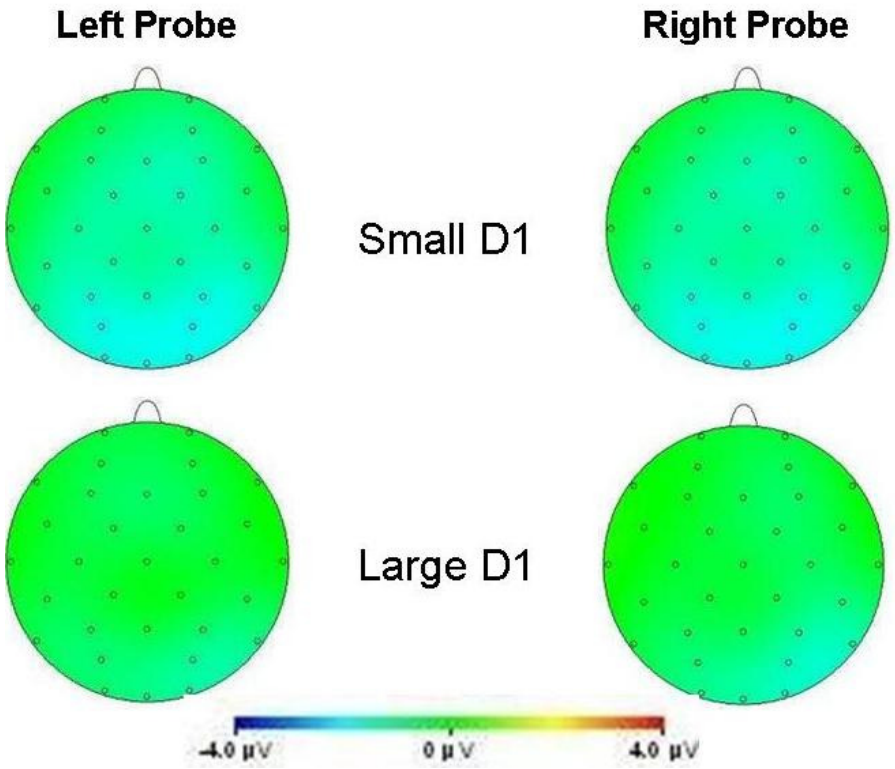

Figure 29. Scalp Distributions to Late Probes 0 – 100 ms Post-Stimulus. ERP scalp distributions (in the time window 0 ms – 100 ms post-probe onset) for late probes appearing in left or right visual field and following small or large D1 cues.

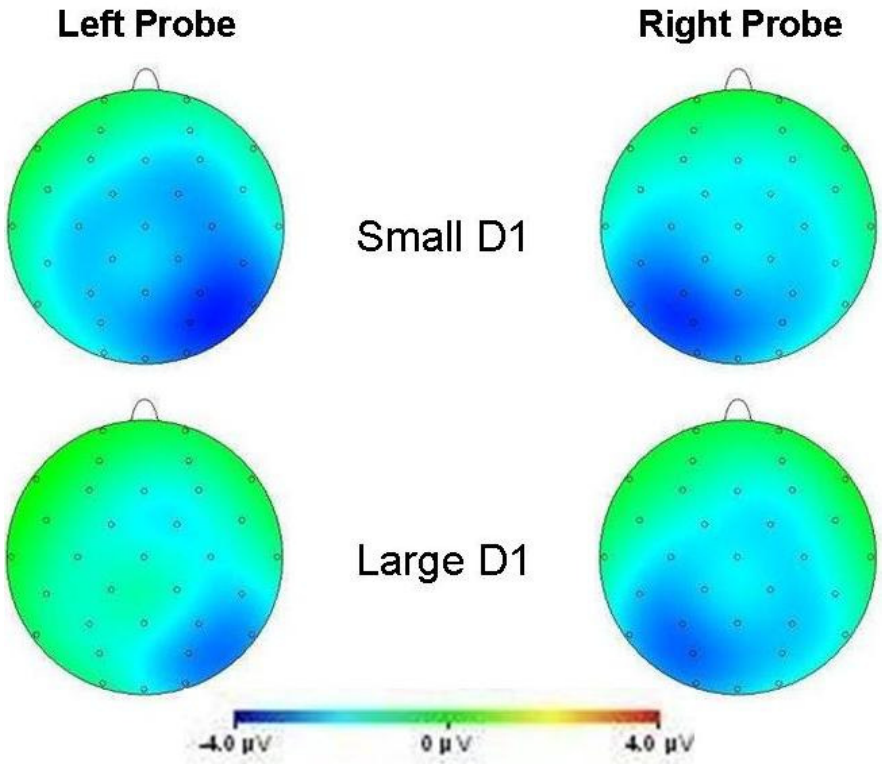

Figure 30. Scalp Distributions to Late Probes 100 – 200 ms Post-Stimulus. ERP scalp distributions (in the time window 100 ms – 200 ms post-probe onset) for late probes appearing in left or right visual field and following small or large D1 cues. Scalp maps show maximal negativity at posterior sites contralateral to visual hemifield in which probe appeared.

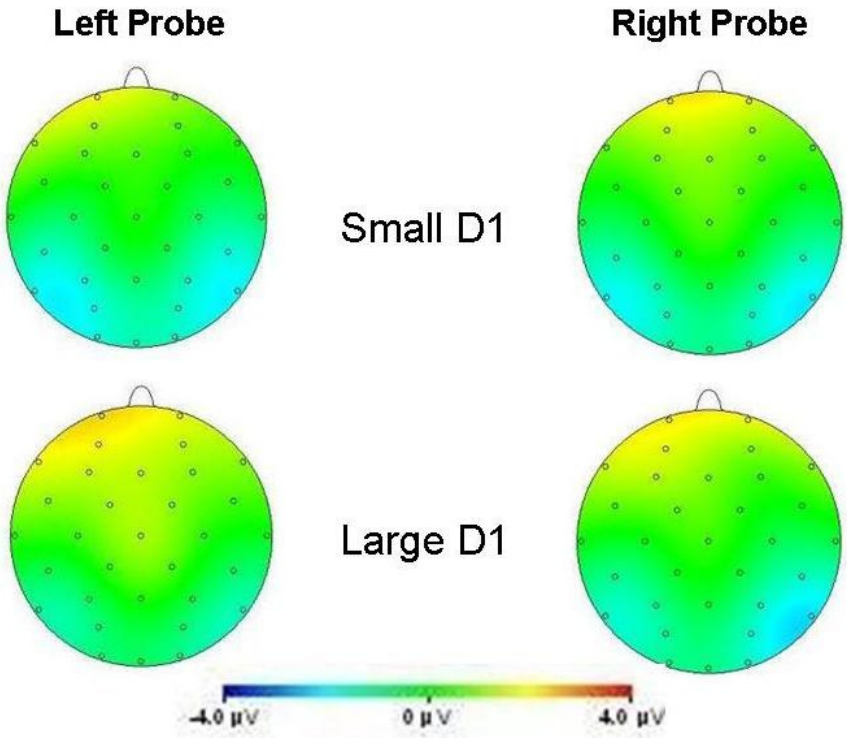

Figure 31. Scalp Distributions to Late Probes 200 – 300 ms Post-Stimulus. ERP scalp distributions (in the time window 200 ms – 300 ms post-probe onset) for late probes appearing in left or right visual field and following small or large D1 cues.

Summary and Discussion ERP Results Experiment 2

Based on the notion that attentional shifts can be elicited by digit pre-cues in accordance with a mental number line associating small-magnitude numbers with left-space and large- magnitude numbers with right-space, and with a few previous experiments with simple detection paradigms showing evidence consistent with this notion, it was expected in the present experiment that ERPs to task-irrelevant visual probes would be modulated in an interaction of visual hemifield with D1 pre-cue magnitude. Specifically it was expected that ERPs would be enhanced to left-side probes following small D1 pre-cues and to right-side probes following large D1 pre-cues. Additionally it was expected that these effects might differ across probes appearing relatively early or late in the D1- D2 interval (100 ms and 450 ms after D1 onset, respectively), on the assumption that responses to early and late probes would reflect differing degrees of exogenous versus endogenous attentional cuing, respectively.

The ERPs to the early probes were distorted due to overlapping ERPs evoked by the preceding D1 and were not useful for evaluating the research hypothesis. In contrast, the ERPs to the late probes appeared more typical, with an evident negative peak occurring in the interval 100 – 200 ms following the probes. This peak possibly corresponded to the visual N1 component, which has been shown to be sensitive to variation in attention (Luck et al., 2000). There was a possible trend in this time window for more negative ERPs following small- versus large-magnitude digit pre-cues.

The ERPs to the late probes did not provide clear support for the research hypothesis that ERPs would be enhanced in a SNARC-like manner, i.e., enhanced for left-probes after small digit pre-cues and for right-probes after large digit pre-cues. However, the waveforms to the late probes also showed evidence of artifactual distortion,

showing a general pattern of negative-going drift and apparent separation at time-point zero, undermining possible conclusions.

The simplest explanation for the doubtful quality of the ERP waveforms in this experiment is that the numbers of trials contributing to them (maximum 48 per individual) were grossly insufficient to achieve an adequate signal-to-noise ratio for examining relatively small ERP components such as visual P1 or N1, which typically require upwards of 200 trials to be reliable (Luck, 2005b). Thus for the purposes of this discussion, any conclusions from the ERPs must be tenuous and provisional.

However, the scalp maps depicting the distribution of cortical response across the head at three time points after the visual probes might provide some limited support for the validity ERPs to the late probes. Specifically, scalp maps in the time interval corresponding to the apparent peaks in the waveforms showed maximal negativities at posterior recording sites contralateral to the probe locations, consistent with the typical distribution for the N1. In contrast, scalp maps during the earlier time window in which apparent separation of waveforms was noted did not show such regional specificity.

The classical "size effect" in number comparison tasks takes the form of faster RTs to decide which of two numbers is larger, if both numbers are relatively small (e.g., '1' versus '3') compared to when both numbers are relatively large (e.g., '7' versus '9') even if the numerical "distance" between the two numbers is the same in both comparisons (Cohen-Kadosh, 2008). If the tentative result disclosed in the present exploration, the trend for enhanced ERPs to late probes after small D1 pre-cues, is taken at face value, this result might suggest a mechanism of greater cortical activation in response to viewing relatively small numbers compared to large ones that would partly

explain the classical "size effect." It might be fruitful to further investigate this intriguing and novel possibility in future experiments designed to explain the numerical "size effect."

All the same, there was only a trend for enhanced negativity following small versus large digit pre-cues. Furthermore, even if this trend were to be taken at face value, it is unclear whether it is specifically related to numerical magnitude or to other stimulus characteristics. Specifically, although the visual stimuli eliciting the ERPs were physically identical except for their spatial location, the number stimuli just preceding them in time were not physically identical. It cannot be assumed that the different stimulus characteristics of the digit pre-cues did not have relatively long-lasting differential effects on the ERPs evoked by subsequent probes (Luck, 2005b). Therefore the visual ERPs to the peripheral probes after small and large digit pre-cues might be distorted by differential responses to the physical shapes of '1' and '3' versus '7' and '9' respectively. This deficiency could be easily remedied in future experiments by varying the ranges of numbers defining "small" and "large."

Taking the results at face value, contrary to the research hypothesis there was no evidence for an interaction of visual hemifield and D1 magnitude for ERPs evoked by the task-irrelevant visual probes. Thus the present experiment shows a failure to generalize ERP findings of attentional shifts associated with digit pre-cues from simple target detection tasks in previous work (Sallilas et al., 2008; Ranzini et al., 2009) to the number comparison task in the present work. Thus, the present findings seem to partly undermine the idea that processing numerical information automatically biases attention according to a mental number line that associates small numbers with left space and large

numbers with right space. If such automatic shifts of attention occurred in the present experiment, they went undetected by the ERPs that were obtained by probing visual responses after participants had to encode and interpret a numerical stimulus.

A possible explanation for the absence in the present experiment of SNARC-like effects on visuospatial attention from digit pre-cues can be articulated based on the modified dual-route model of SNARC effects that was applied in the discussion of Experiment 1. Recall that to account for performance of the number comparison task, it was assumed that fast automatic activation of a spatial representation in response to D1 magnitude was suppressed in order to prevent premature responses. This mechanism would operate likewise in the task in Experiment 2, and would likely tend to nullify visuospatial biases related to a mental number line concept during the D1-D2 interval.

Alternatively, Wood and Fischer (2008) drew attention to the empirical fact that that SNARC-related effects tend to be observed for response-selection, and not for earlier processes related to visuospatial attention, when numerical information determines the response to be executed, as in the standard parity task or the number comparison tasks in the present experiments. In contrast, attention-SNARC effects have been so far observed when numerical information is task-irrelevant and encoded only incidentally, as in the target detection task with digit pre-cues (Wood & Fischer, 2008).

On a more general level, this empirical pattern is consistent with the view that spatial reference frames for perception and for action are coded by different neural populations (Milner & Goodale, 2006). The present experiment was intended in part to yield positive evidence that would falsify this inductive generalization. SNARC interference was observed for RTs in the number comparison task, indicating that spatial-

numeric associations were operating again in the realm of response-selection. However, no SNARC-like attentional effects were observed. These results are consistent with the above hypothesis of Wood and Fischer (2008), although they cannot be counted as positive evidence.

However, the conjecture by Wood and Fischer (2008) can be undermined by noting some additional evidence against it in the literature (Dodd, van der Stigchel, Leghari, Fung & Kingstone, 2008). Dodd and colleagues (2008) compared the attention-directing properties of digit pre-cues in simple target detection against other terms denoting ordinal relationships (e.g., letters, days of the week). Non-numerical terms appeared to cue attention shifts according to a directed spatial representation, analogous to the mental number line, only when participants were required to process the ordinal information of the pre-cues; whereas digit pre-cues did so regardless of whether their ordinal content was implicitly or explicitly processed.

Another possibility for the present failure to find attention-related effects in the ERPs evoked by peripheral visual probes lies in the fact that in contrast to the previous target detection experiments cited (Ranzini et al., 2009; Salillas et al., 2008), processing the peripheral stimuli in the present experiment (as well as the locations at which they appeared) was task-irrelevant (and participants were instructed to ignore them), regardless of whether processing the numerical information was task-relevant or task-irrelevant. Furthermore, participants were concurrently engaged at fixation with performing the attention-demanding number comparison task, which may have left few attentional resources for processing events occurring in the periphery (Lavie, 2010). Another possibility is that the peripheral visual probes in the present experiment provided

visual stimulation that was simply too weak to provide a sensitive index of visuospatial attention.

The present investigation can be situated in the larger context of investigations of the properties of objects/events that cause individuals to orient attention to a particular region of space. Traditionally, attentional cues been classified as "exogenous" and "automatic" or "endogenous" and "voluntary," corresponding to classical distinctions in cognitive psychology (Wright & Ward, 2008). Attention is said to be "captured" by exogenous cues such as a bright flash appearing in the periphery. Attention is said to be voluntarily directed to a peripheral location after interpreting a symbol, such as an arrow, appearing in central vision. However, recent research and theory have complicated this framework.

Gibson and colleagues have questioned the general continued theoretical utility of the influential exogenous/ endogenous distinction, advocating instead a contrast between "projective" cues, such as verbal instructions (words), that require semantic interpretation in relation to a selected spatial reference frame, and "deictic" cues, including arrows, sudden-onset flashes, and eye-gaze cartoons, which operate on attention more directly without the need for "imposing a reference frame on the cue" (Gibson & Kingstone, 2006; p 626). Within this framework, whether a spatial reference frame is evoked by numbers projectively or deictically depends on whether the mental number line concept is activated directly upon presentation of a digit, or after mediation by a spatial reference frame constructed due to culture and language. This remains a crucial open question for future research to address.

CHAPTER 7

GENERAL DISCUSSION

This paper reports two ERP experiments investigating spatial-numeric associations. The first experiment was focused on associations between numerical magnitude and locations in "response space" conceived in terms of left-right coordinates of the body and especially the hands. The second experiment was focused on associations between numerical magnitude and locations in visual space, conceived in terms of left-right coordinates of the visual field. The key findings are reviewed below, followed by more general implications of the experiments.

Experiment 1 found that the SNARC effect in a number comparison task was attenuated for behavioral RTs when the first number gave complete information about the response that would be required after viewing the second number. LRPs showed greater negativity after the presentation of the first number in this condition. LRPS were not modulated by SNARC interference before the presentation of the second number to be compared. In the time interval 200 ms – 400 ms after the presentation of the second number, LRPs were more negative for SNARC-compatible conditions, even when complete advance information about the required response had been communicated by the first number. In roughly this same time interval, the P300 component showed robust effects of SNARC-compatibility as well as expectancy. When examining later stages of cortical activation with more fidelity in LRPs time-locked to response offset, no SNARC effects were found.

However, lower prior response-probability was related to steeper (more negative) LRP slopes, and steeper slopes were predictive of faster behavioral RTs. Interestingly, LRP slopes were selectively associated with behavioral RTs in SNARC-compatible conditions, which may suggest an underlying effect of SNARC during late response-

execution phases that is observable at the level of individual differences but is obscured when making group comparisons.

Overall, results were consistent with those from a limited amount of previous ERP research into SNARC effects (Gevers, Ratinckx et al., 2006; Keus et al., 2005), showing that SNARC interference arises and is resolved at relatively intermediate stages of response-selection. The present experiment also yielded the novel finding of P300 modulation by SNARC-compatibility as well as expectancy. This result is possibly evidence for posterior parietal involvement in generating and resolving SNARC interference.

The ERP results of Experiment 1 found SNARC effects only after presentation of the second number to enter into comparison, but not after the presentation of the first number. This was explained by invoking a mechanism to suppress fast automatic activation of a spatial reference for the first number, in order to prevent premature responses. When the second number was presented, there was no longer any requirement to withhold responding and SNARC interference was then observable in the ERPs, regardless of the level of facilitation for response-selection due to prior information. Thus, the ERPs were able to disclose SNARC-related differences in cognitive processing even when response-cuing was certain, which were not detectable by behavioral RTs alone.

Experiment 2 took a different approach to investigating spatial-numeric interactions, by presenting task-irrelevant visual events occurring in left or right visual fields during the time interval between the two numbers in the comparison task. It was predicted based on previous work using simple target detection tasks that early visual ERPs would be enhanced to task-irrelevant visual probes appearing in left visual space after relatively small number cues, and to probes appearing in right visual space after relatively large number cues. Results of this experiment were ambiguous, owing to technical deficiencies such as the number of trials contributing to the ERPs. A possible

trend for a "size effect" was disclosed, in which ERPs were enhanced to visual probes after small number cues regardless of visual field. Scalp distributions in the time window in which there were evident peaks in the ERP waveforms were consistent with the expected distribution for the N1 component, which is sensitive to attention (Luck, 2005; Luck et al., 2000). This result, if taken at face value, is intriguing and merits further exploration. However, the results did not show that ERPS were modulated by digit magnitude in a manner that interacted with left/right visual space as was predicted by assuming SNARC-like effects on visual attention.

The experiments occurred at the intersection of a broad array of motivating considerations, briefly reiterated in the following remarks. Quantity and order are two important features of events in the world that can be described by numbers. Comprehending numbers is important for survival and effective action in most contemporary societies. Better understanding of how numbers are represented psychologically and by the brain has potential implications for pedagogy and policy making. There is evidence to suggest that numbers are represented in a spatial format, as in a directed "mental number line" in which small magnitudes are represented on the left and large magnitudes on the right. This association might be viewed as an example of "conceptual metaphor" structures which permeate language and thought, in which abstract concepts like number and time are opportunistically constructed around representational systems for more concrete experiences of space. In this view, abstract concepts like number are represented in a way that is grounded in sensorimotor experience and by the fact of living in a body. This view also highlights the notion that perception and thought are above all in the service of effective action, and not for the sake of cognition as an end.

The association of numbers and space in body-centered spatial coordinates can give rise to consequences for action selection. Choosing to respond with the left hand or the right hand can be hurt by the degree of alignment between the spatial location of the

response and the meaning associated with the response (when e.g., "right" means "small"). Thus, associations between numbers and space are seen to be a source of "bottom-up" influence on behavior that sometimes needs to be counteracted by "top-down" goals. In line with these considerations, "numerate neurons" have been found in frontal and parietal parts of the brain, partly overlapping with brain circuits supporting perception and action. Communication or cross-talk between neural populations coding for quantity, order, and numerosity on one hand, and for spatial attention and spatial response-selection on the other, suggests a possible brain mechanism for spatial-numeric associations; as well as for their consequences for choosing among possible actions in space (or attending to regions of space).

Together, the two experiments were motivated by the broad range of considerations summarized above. The first experiment examined consequences of spatial-numeric associations for action in "response space." The second experiment examined them for visuospatial attention. Extending the investigation across these disparate cognitive domains was motivated by the broader question of interconnections between visual and motor systems and whether these would be similarly or differently affected by spatial-numeric associations. This question can be connected to the larger controversy concerning whether spatial reference frames for perception and for action are coded by different neural populations (Milner & Goodale, 2006) or by the same neural populations (Rizzollatti, Ferrari, Rozzi, & Fogassi, 2006). This remains an important open question for future research.

Two experiments examined effects of spatial-numeric associations in the contexts of response-selection and visuospatial attention, in combination with other variables including prior response-probability, cue-validity, and spatial location. Response-related LRPs showed that compared to prior response-probability, effects of SNARC-compatibility appeared later even when stimulus-response mapping was a constant feature of the task environment. Thus, SNARC effects were not automatically elicited

during early response-selection in advance of the imperative stimulus, but exerted residual effects during later response- selection that was completed after the imperative stimulus. In a separate experiment, attention-related ERPs were not modulated by digit magnitude according to a directed mental number line. Together the experiments suggest that SNARC-like effects are more strongly related to response-selection than to visual attention processes.

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